Nuclear Parton Densities

status & future avenues

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work done in collaboration with D. de Florian, R. Sassot, and P. Zurita: PRD85 (2012) 074028
(arXiv:1112.6324)

Outline

- **Nuclear PDFs 101**
  framework, experimental input, main features of nPDFs
- **strategies to parametrize nPDFs**
  overview of existing analyses, issues
- **results of our new global QCD analysis**
  what is new, some technical aspects, comparison to data & other fits
- **future avenues in dA (pA) collisions at RHIC (LHC)**
  prompt photons, Drell Yan

foundation: pQCD & factorization

QCD improved parton model - a success story ever since

- describes quantitatively a large variety of hard processes in e^+e^-, ep, pp, ...
- **key assumption**: factorization of long- and short-distance physics
  corrections: inverse powers of large scale

$$\frac{d\sigma}{dp_T} = \sum_{ab} \underbrace{f_a(x_a,\mu) \otimes f_b(x_b,\mu)}_{\text{from experiment}} \otimes \underbrace{d\hat{\sigma}_{ab}(\mu)}_{\text{calculable}} + \mathcal{O}\left(\frac{1}{p_T^n}\right)$$

- predictive power
- **systematic framework** to compute higher order corrections
  NLO standard; NNLO known or on the horizon

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- predictive power
- **systematic framework** to compute higher order corrections
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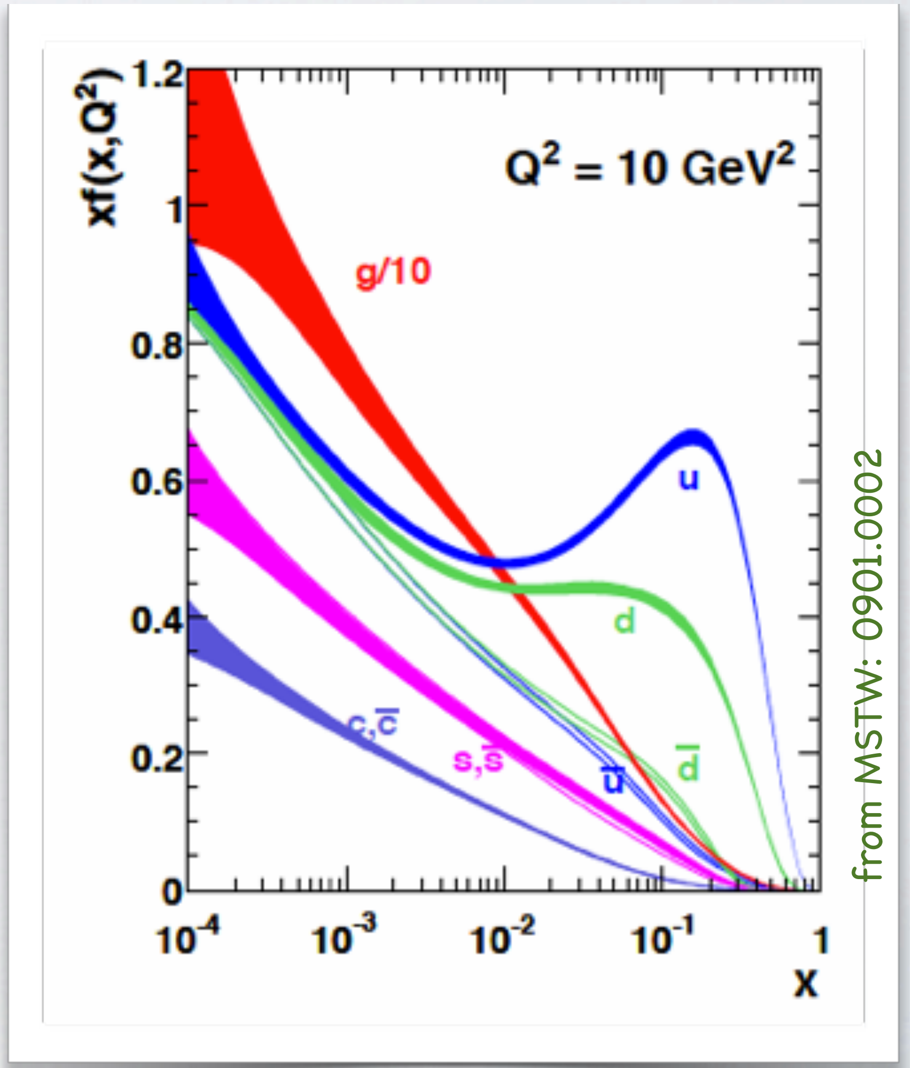
- small amount of phenomenological parameters to be determined from data
  parton densities, masses, α_s, fragmentation fcts.



from MSTW: 0901.0002

parton content of **free** protons
rather well known by now in broad x,Q^2 range
some fine details are missing though

PDFs for bound nucleons

main idea:

- keep standard pQCD framework and **assume factorization** also for nuclei $$\frac{d\sigma}{dp_T} = \sum_{ab} f_a(x_a,\mu) \otimes f_b(x_b,\mu) \otimes d\hat{\sigma}_{ab}(\mu) + \mathcal{O}(\frac{1}{p_T^n})$$

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- DGLAP scale evolution
- hard scattering cross sections

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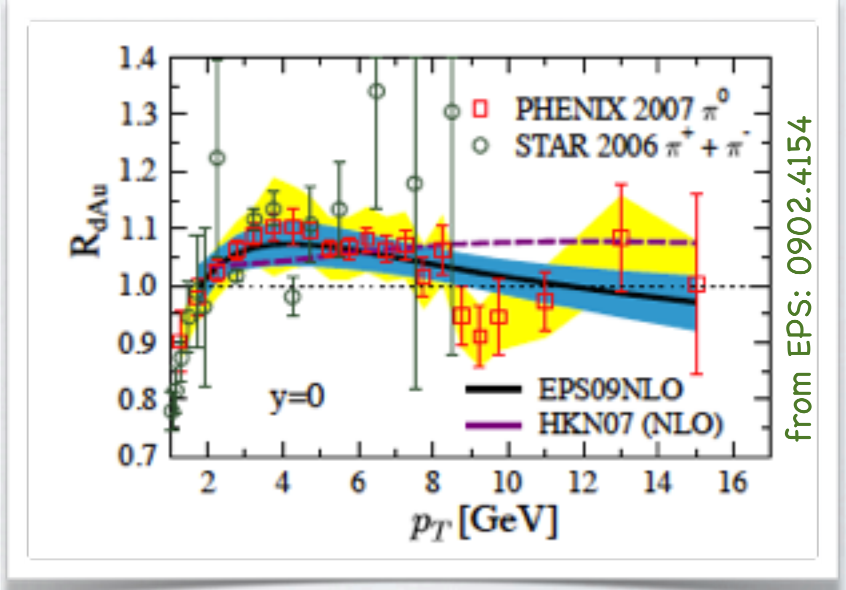
- **complication** (often happily ignored): nuclear modifications of final-state hadrons
  hard to accommodate (modified fragmentation?)



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- nPDFs can parametrize nuclear effects with little bias and without assuming certain “mechanisms” to model the observed modifications/effects
  link to models of nucleon structure at low scales and proposed nuclear modifications
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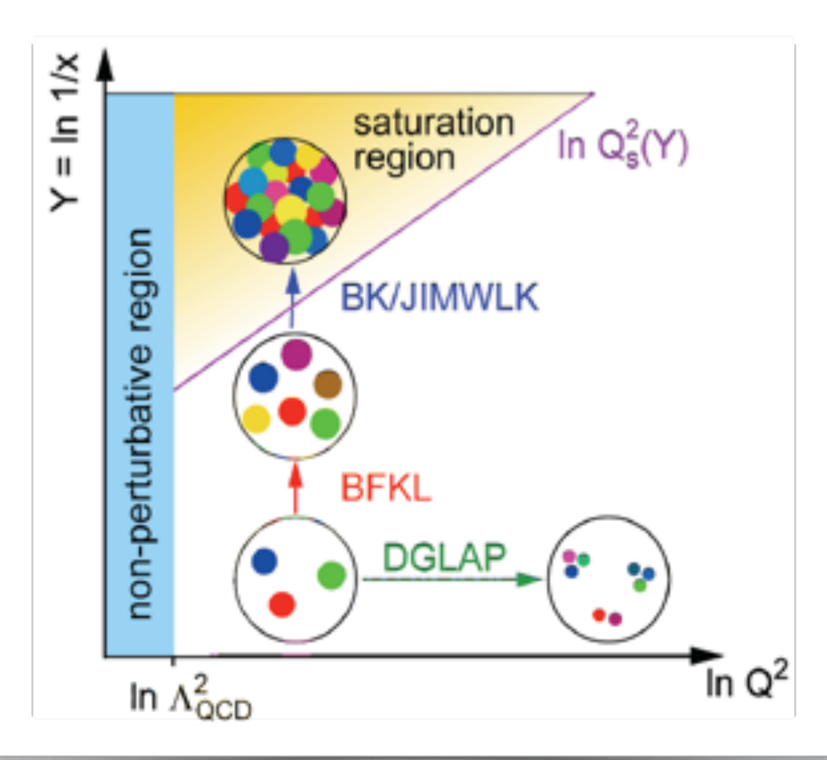
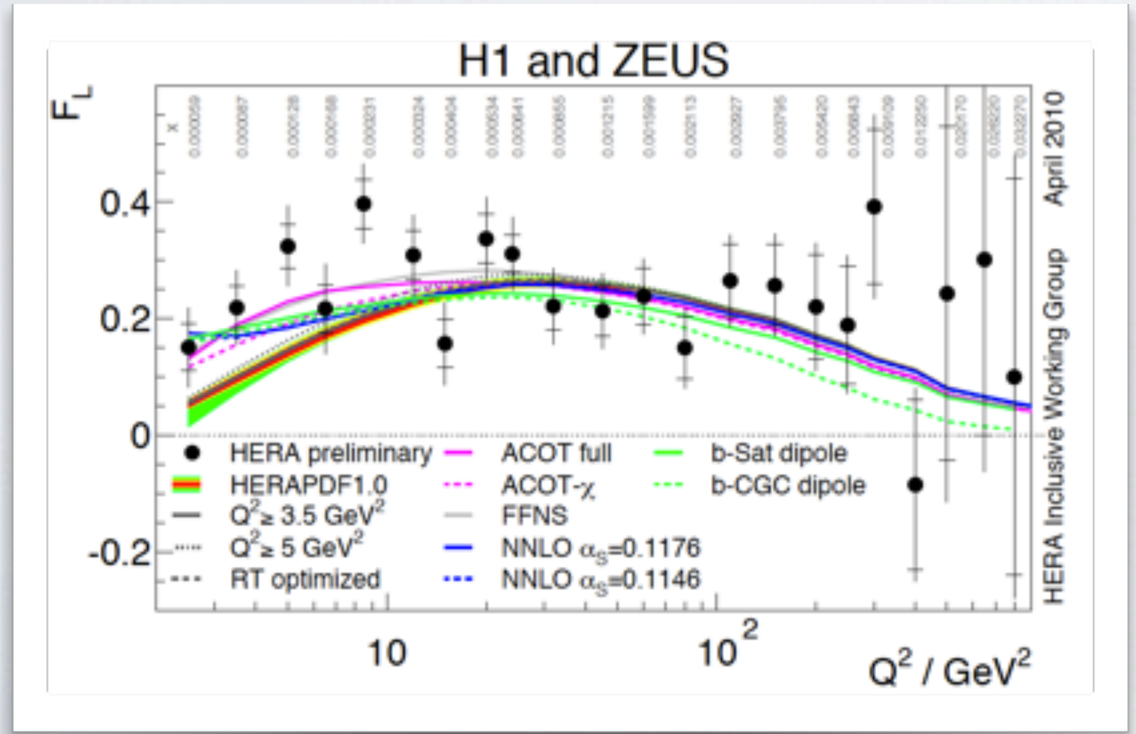
- map out kinematic regime where nPDF framework applies and study transition to saturation region
  - transition often characterized by "saturation scale" $Q_s(x,A)$
  - non-linear effects (recombination) demanded by unitarity

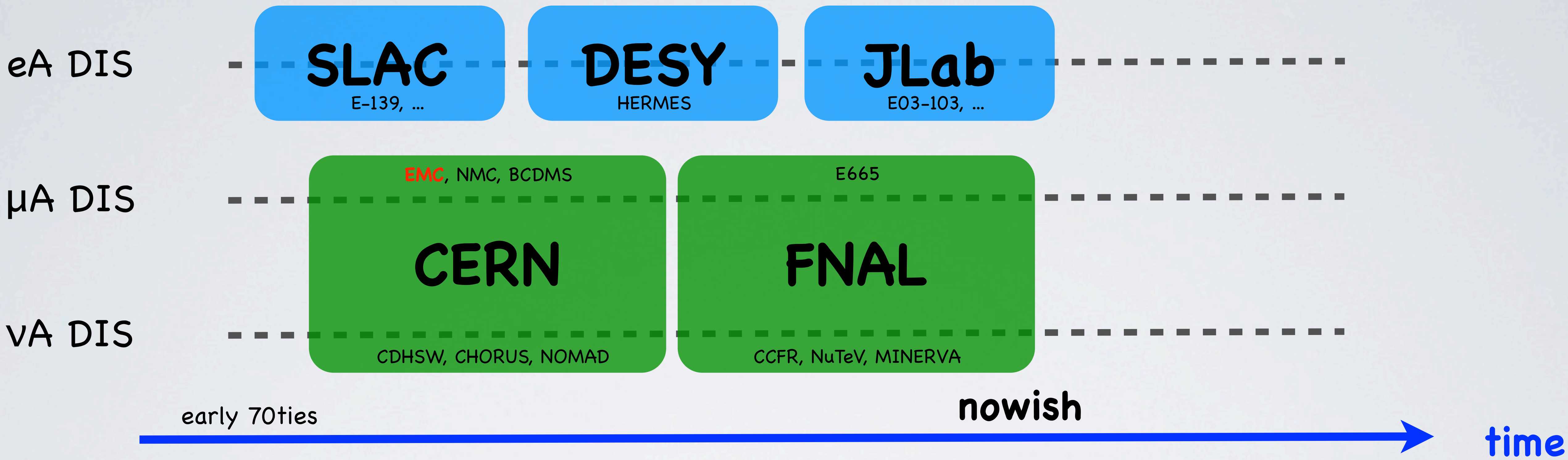




- no unambiguous hints for saturation in ep down to $x = 10^{-5}$
- most promising so far: RHIC hadron yields in dAu collisions
- effects amplified in eA/pA collisions; "nuclear oompf" $\propto A^{1/3}$

experimental input

thriving experimental programs since the early seventies



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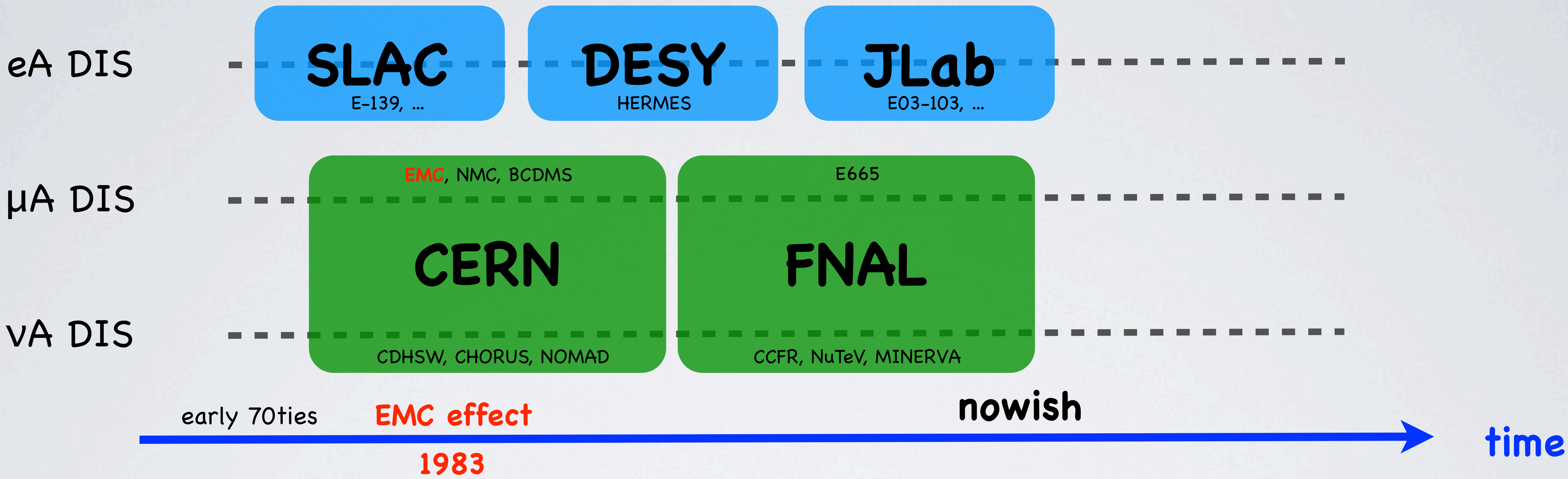

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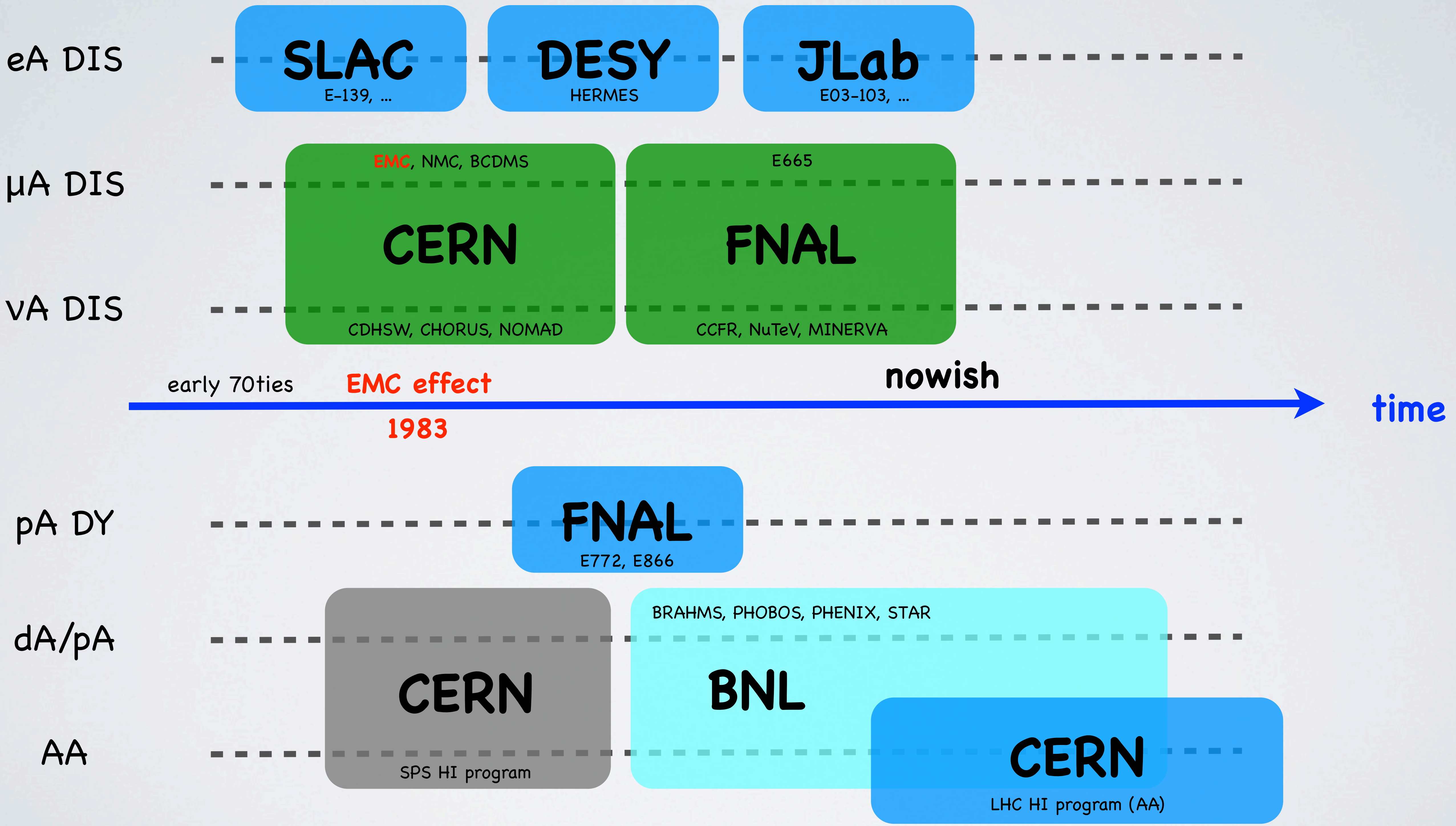

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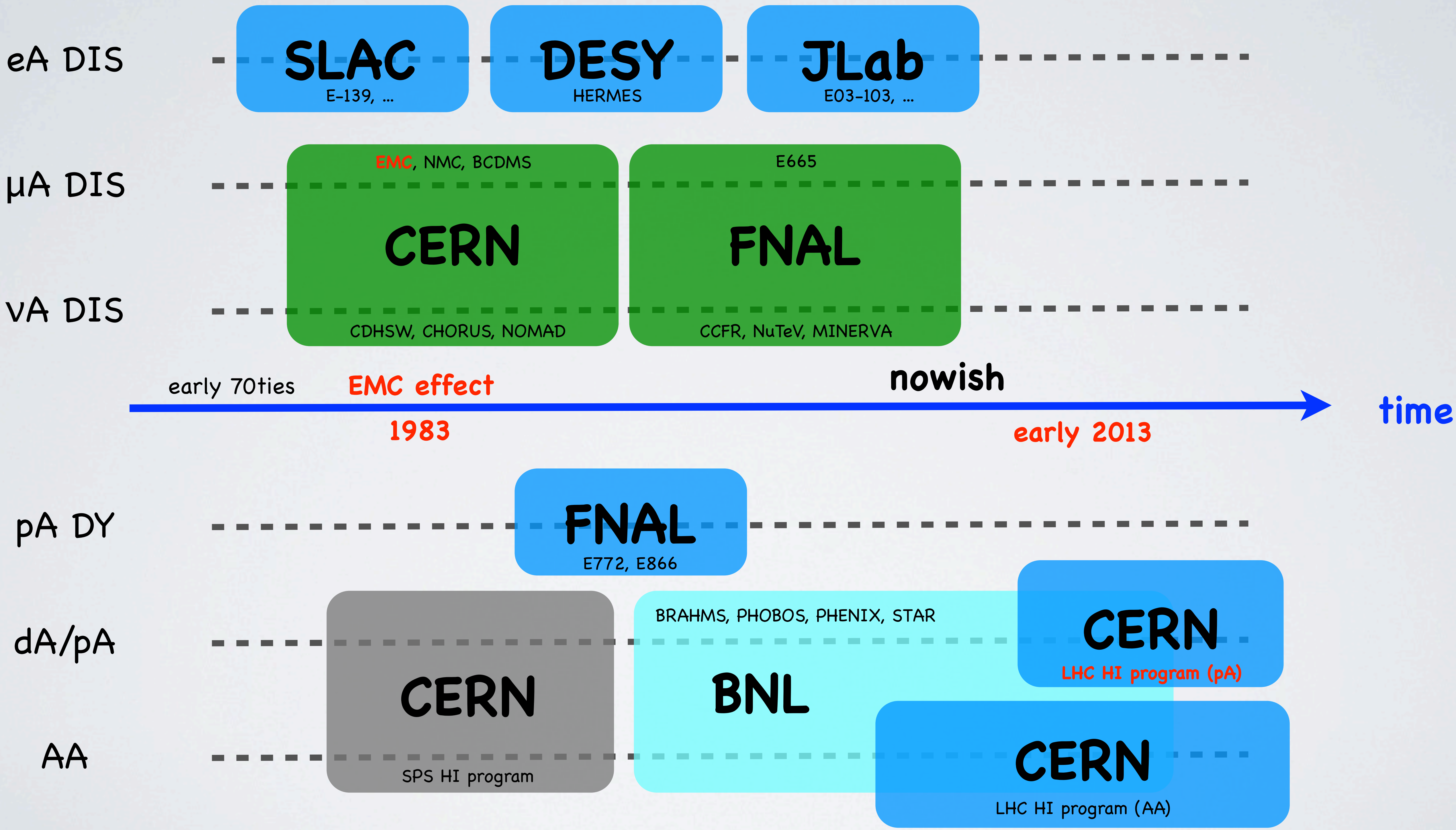

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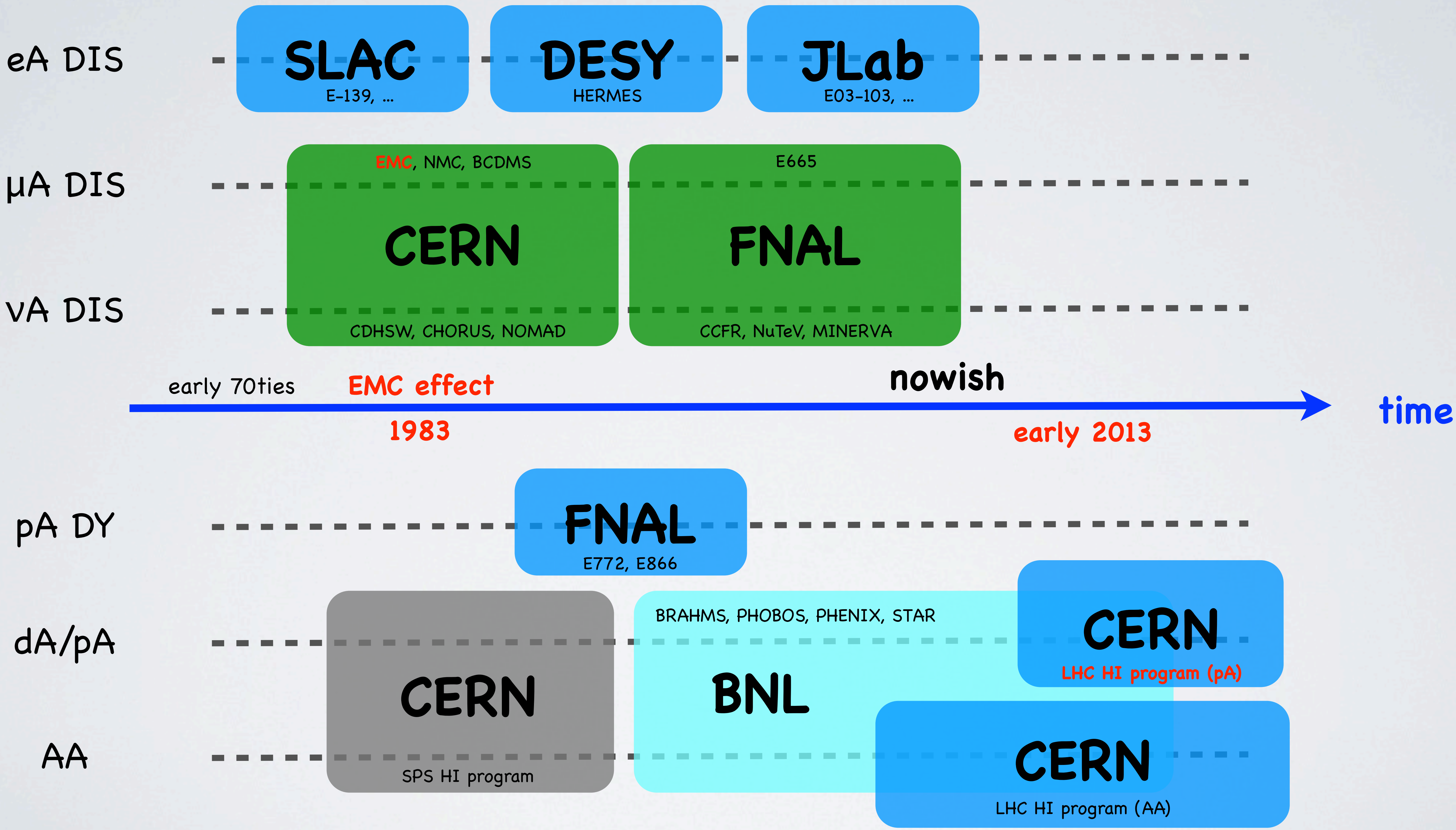

biggest obstacle for nPDF analysis: no eA collider yet

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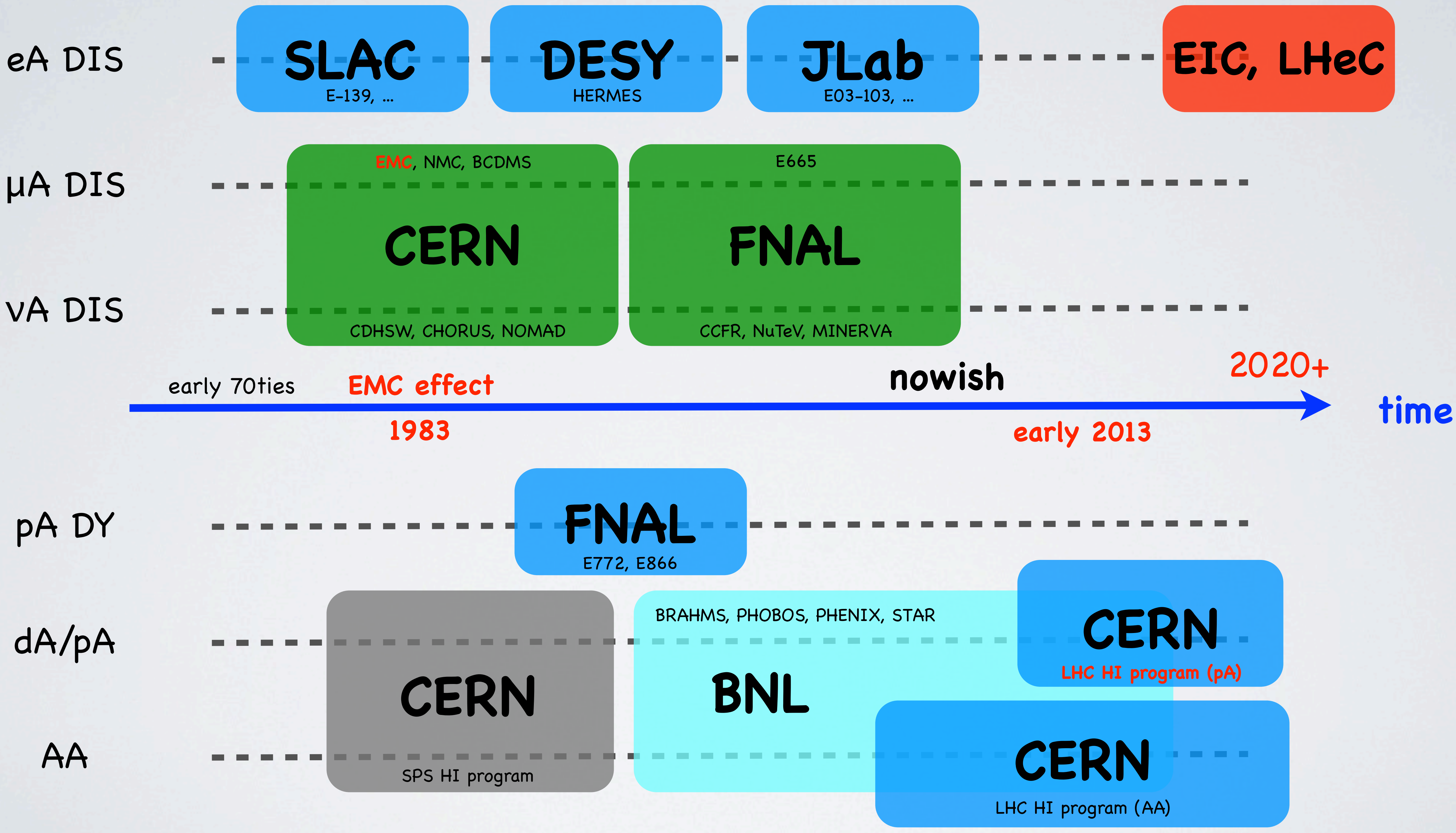

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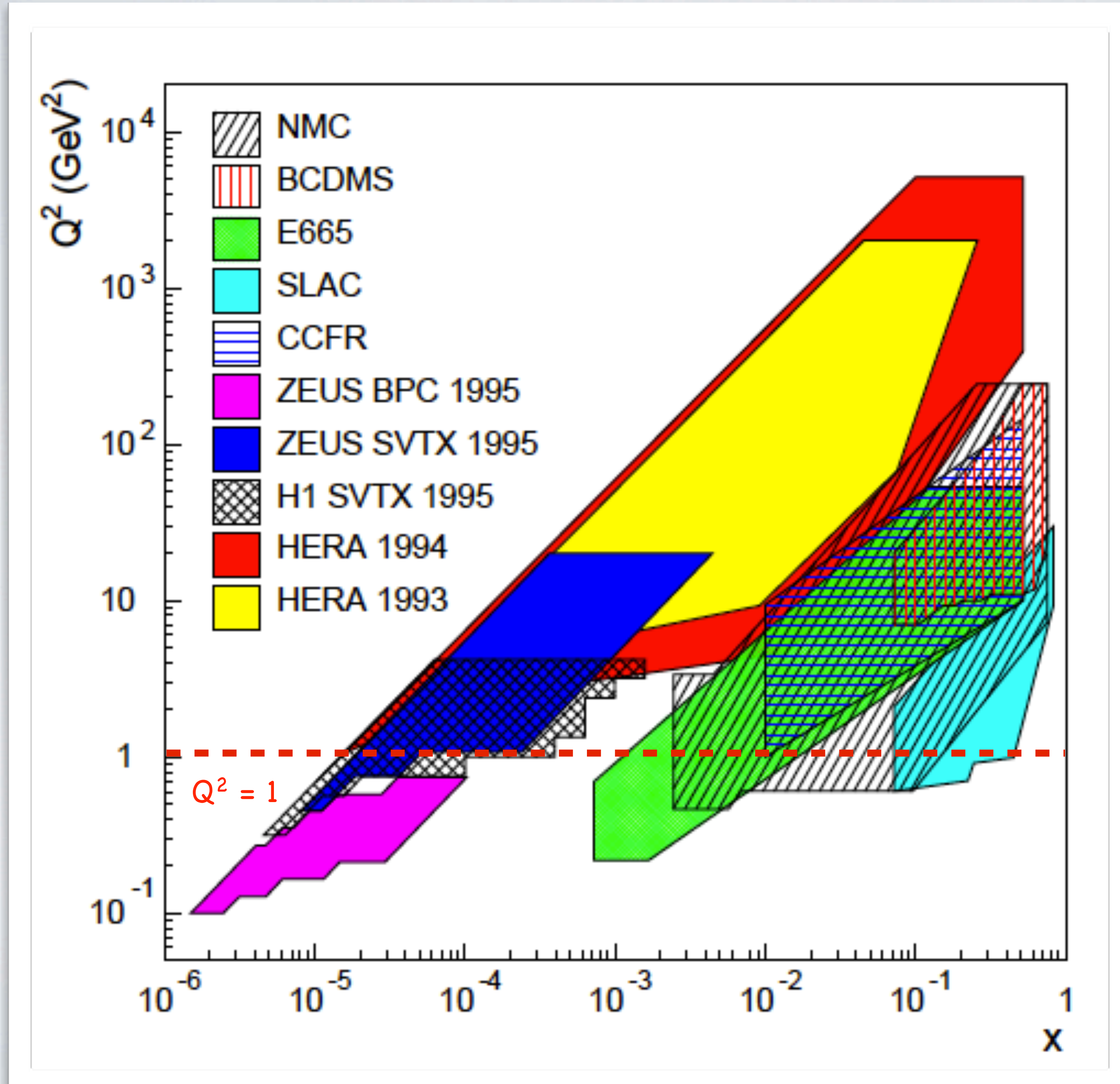
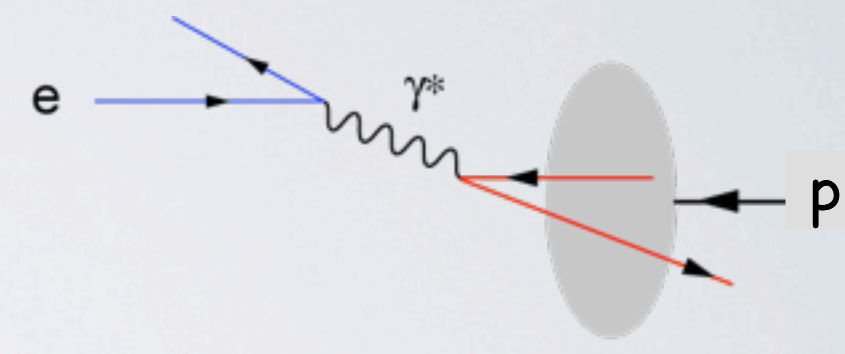


current kinematic coverage for electron-proton DIS



determines small-x behaviour of quarks and gluons in all analyses of proton PDFs

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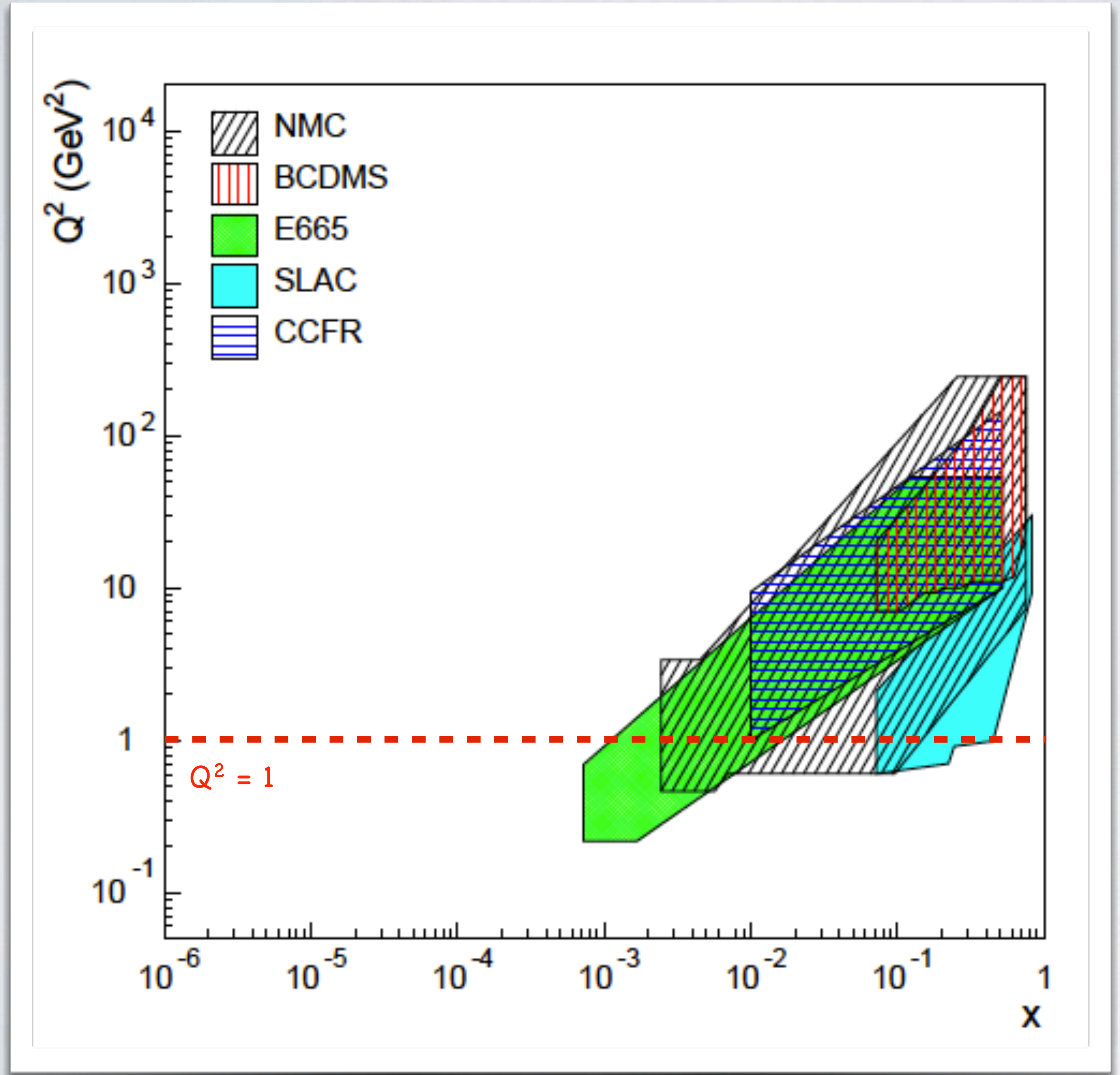
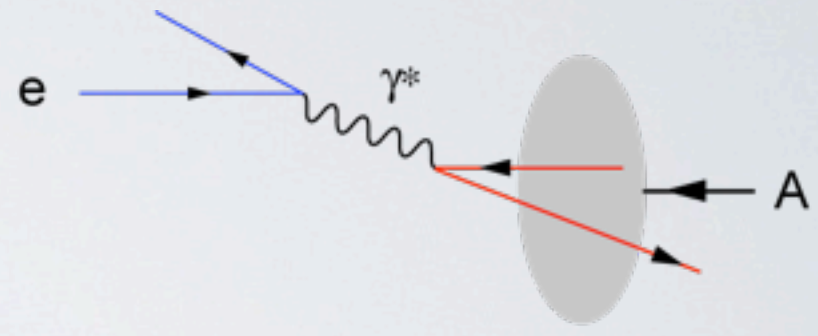


much more limited coverage in eA DIS



yet, the best constraint for nPDFs

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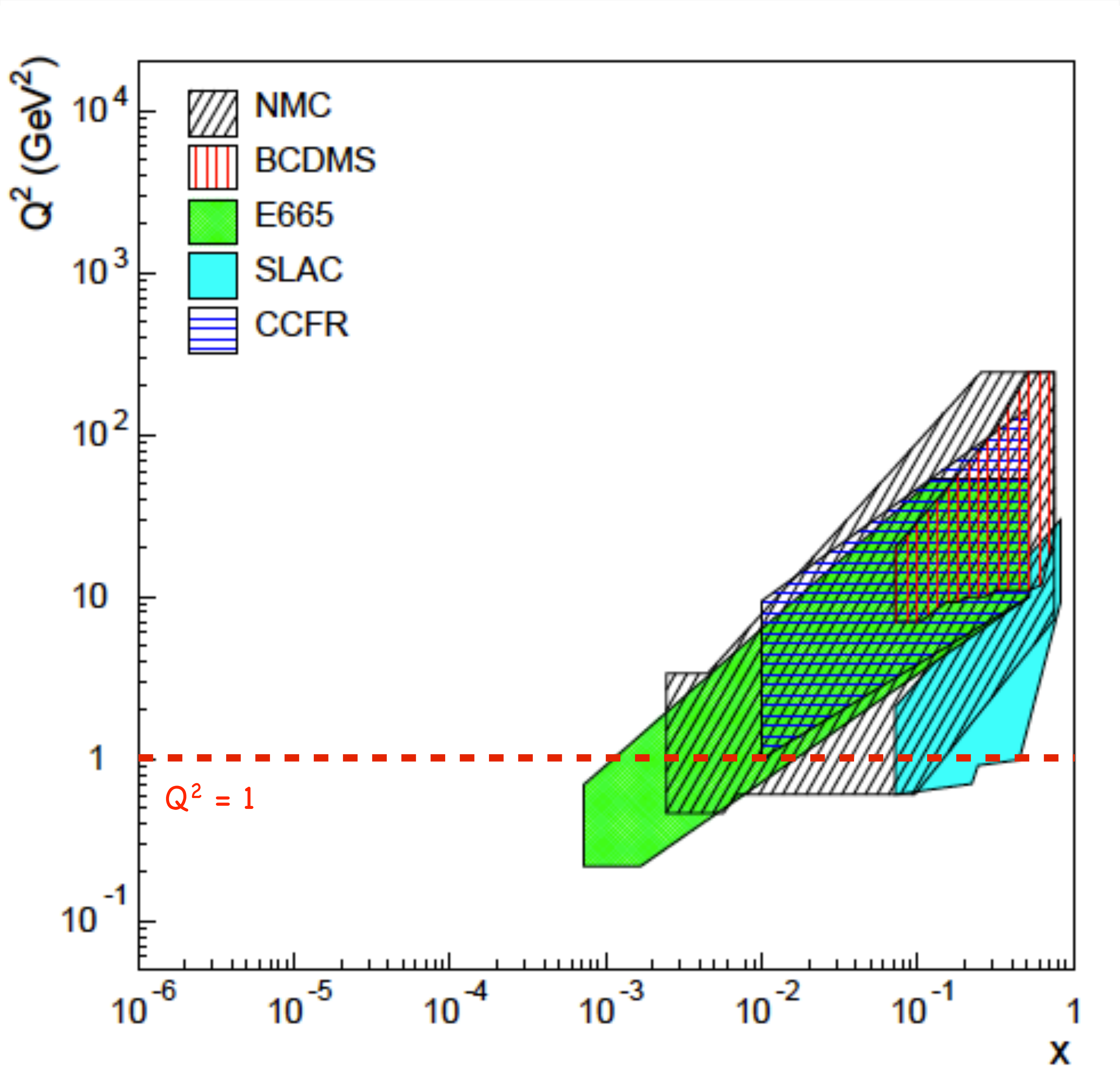

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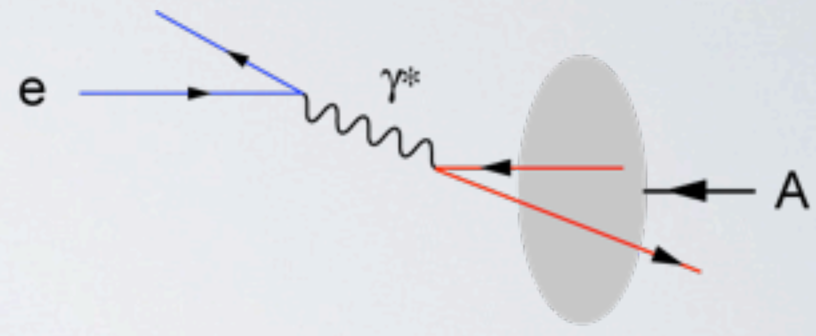


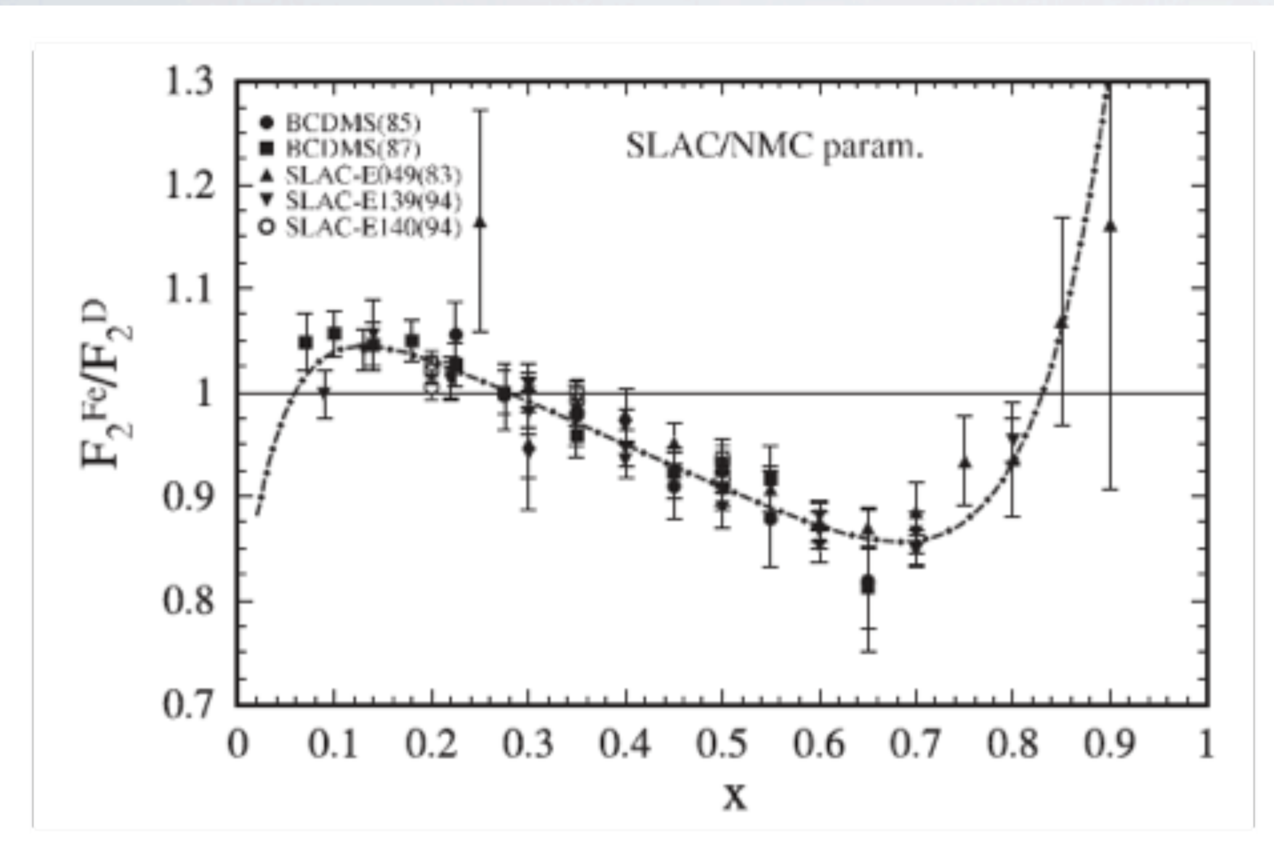
yet, the best constraint for nPDFs

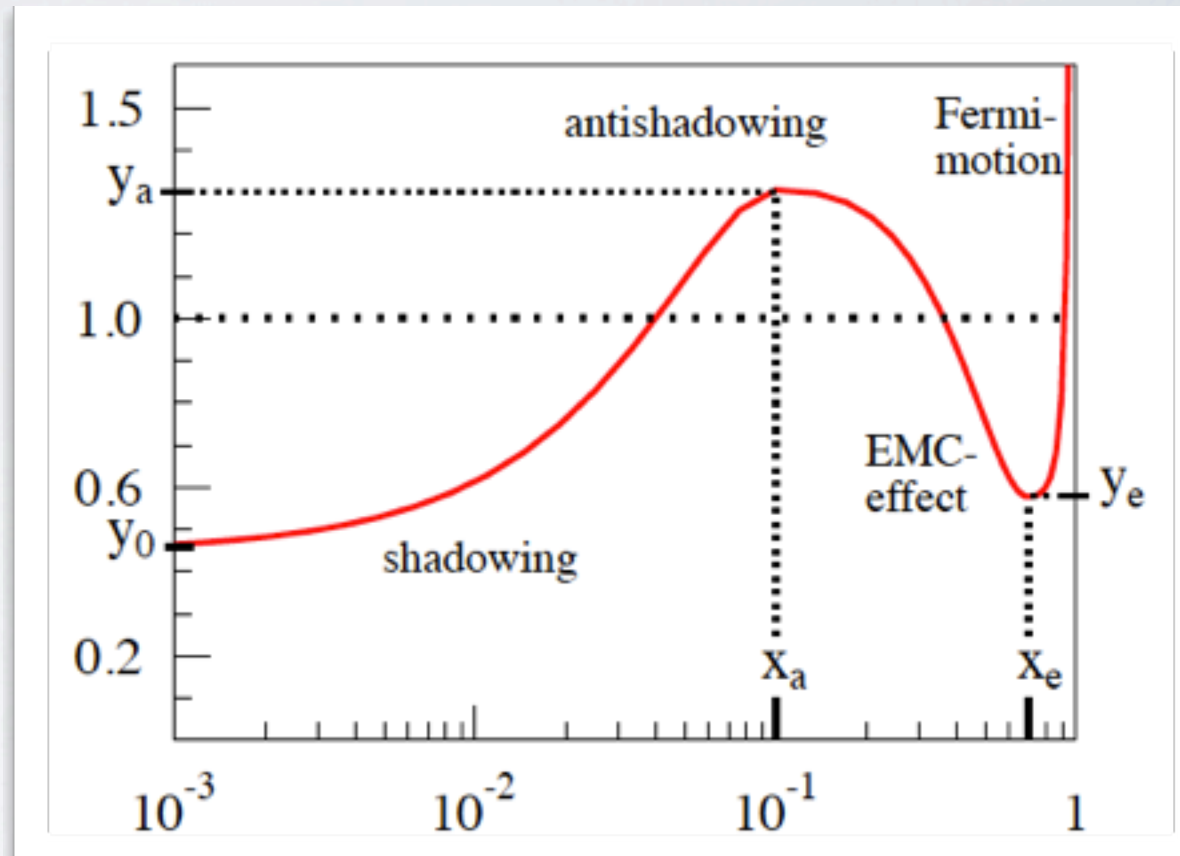
- low x, low Q^2
  where saturation is relevant
- high Q^2
  to test scale evolution

an electron-ion collider
(EIC, LHeC projects)
is in high demand

the many facets of nPDFs

nuclei behave rather differently than a simple incoherent superposition of protons and neutrons → quarks and gluons in bound nucleons exhibit highly non-trivial momentum distributions





nuclear modifications traditionally parametrized as ratios

$$f_i^A(x_N, Q_0) = R_i^A(x_N, Q_0) \times f_i^p(x_N, Q_0)$$

scaling variable (per nucleon) $p_N = p_A/A$

$$x_N = \frac{Q^2}{2p_N \cdot q} \qquad 0 < x_N < A$$

strategies to parametrize nPDFs

all **measurements** usually given in terms of ratios w.r.t. some light nucleus

e.g. $\mathbf{R_A(x_N, Q^2) = \frac{F_2^A(x_N, Q^2)}{F_2^D(x_N, Q^2)}}$

where $\mathbf{F_2^A = \frac{1}{A}\left[Z\,F_2^{p/A} + (A-Z)\,F_2^{n/A}\right]}$

- nPDFs give distributions in bound proton $\mathbf{f_i^{p/A}(x_N, Q^2)}$
- ... assume isospin invariance for $\mathbf{f_i^{n/A}(x_N, Q^2)}$

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conventional ansatz

input scale of O(1 GeV)

free proton densities

multiplicative nuclear correction factor $\mathbf{f_i^{p/A}(x_N, Q_0) = R_i^A(x_N, Q_0) \times f_i^p(x_N, Q_0)}$

choose ansatz and determine from data

used in
Hirai, Kumano, Nagai (HKN) arXiv:0709.3038
Eskola, Paukkunen, Salgado (EPS) arXiv:0902.4154
de Florian, Sassot, MS, Zurita (DSSZ) arXiv:1112.6324

- works well with small amount of parameters
- cannot account for $x_N > 1$ region [as free proton PDFs limited to $0 < x_N < 1$]

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direct ansatz

parametrize nPDFs directly $\mathbf{f_i^{p/A}(x_N, Q_0)}$

used in Keppel, Kovarik, Olness, ... (nCTEQ) arXiv:0907.2357

- still dependent on some free proton PDF to compute ratios
- natural to choose same functional form as for proton PDF

convolutional approach

choose ansatz and determine from data

define nPDF through a weight function $\mathbf{f_i^{p/A}(x_N, Q_0) = \int_{x_N}^{A} \frac{dy}{y}\, W_i^A(y, Q_0)\, f_i^p\left(\frac{x_N}{y}, Q_0\right)}$

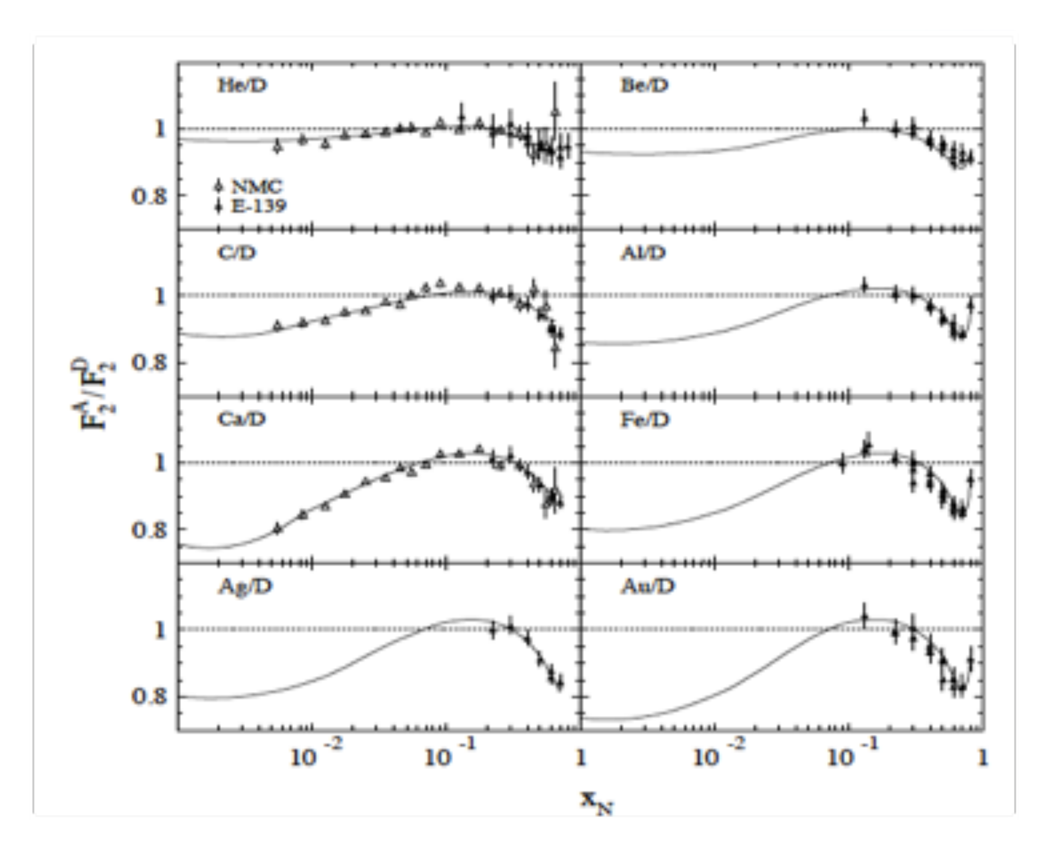
used in de Florian, Sassot (nDS) hep-ph/0311227

- W can be viewed as an effective nucleon momentum density in a nucleus

a brief history of selected nPDF fits

nDS de Florian, Sassot - hep-ph/0311227

- **first NLO analysis** $\chi^2/\mathrm{d.o.f.} = \mathbf{0.74}$
- only SLAC & NMC DIS sets and some DY data
- convolutional approach in Mellin N-space
- no error analysis



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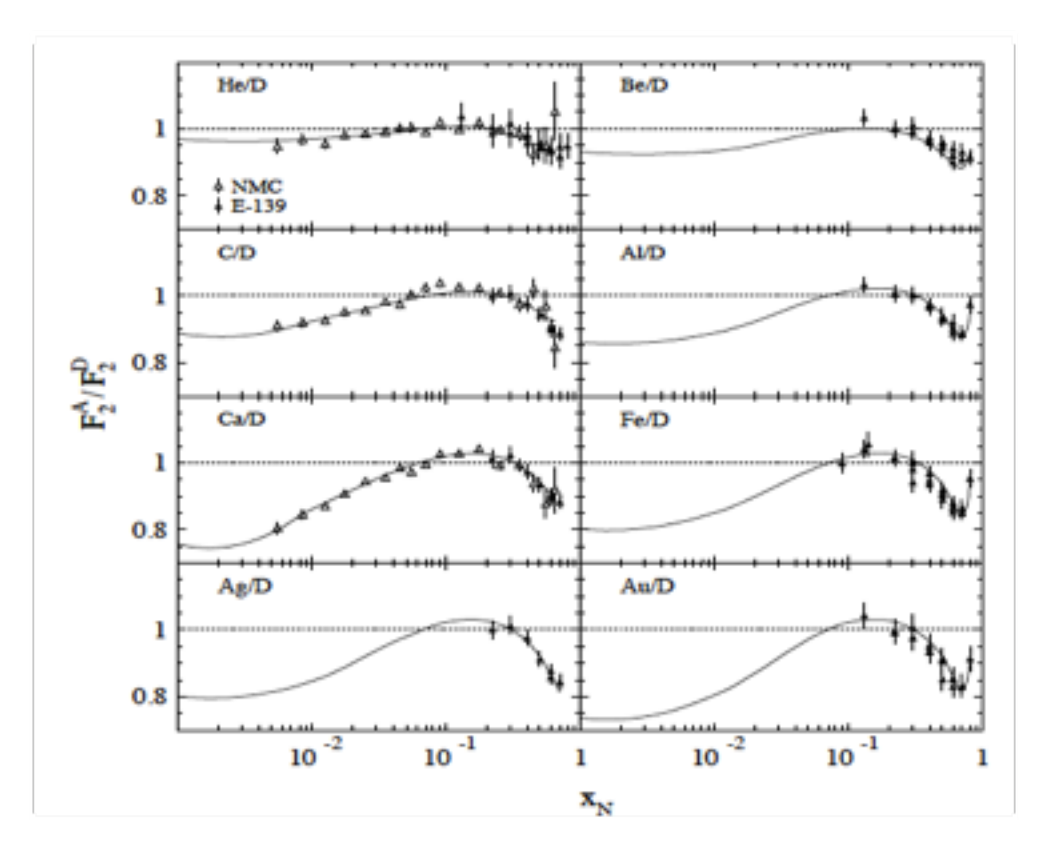

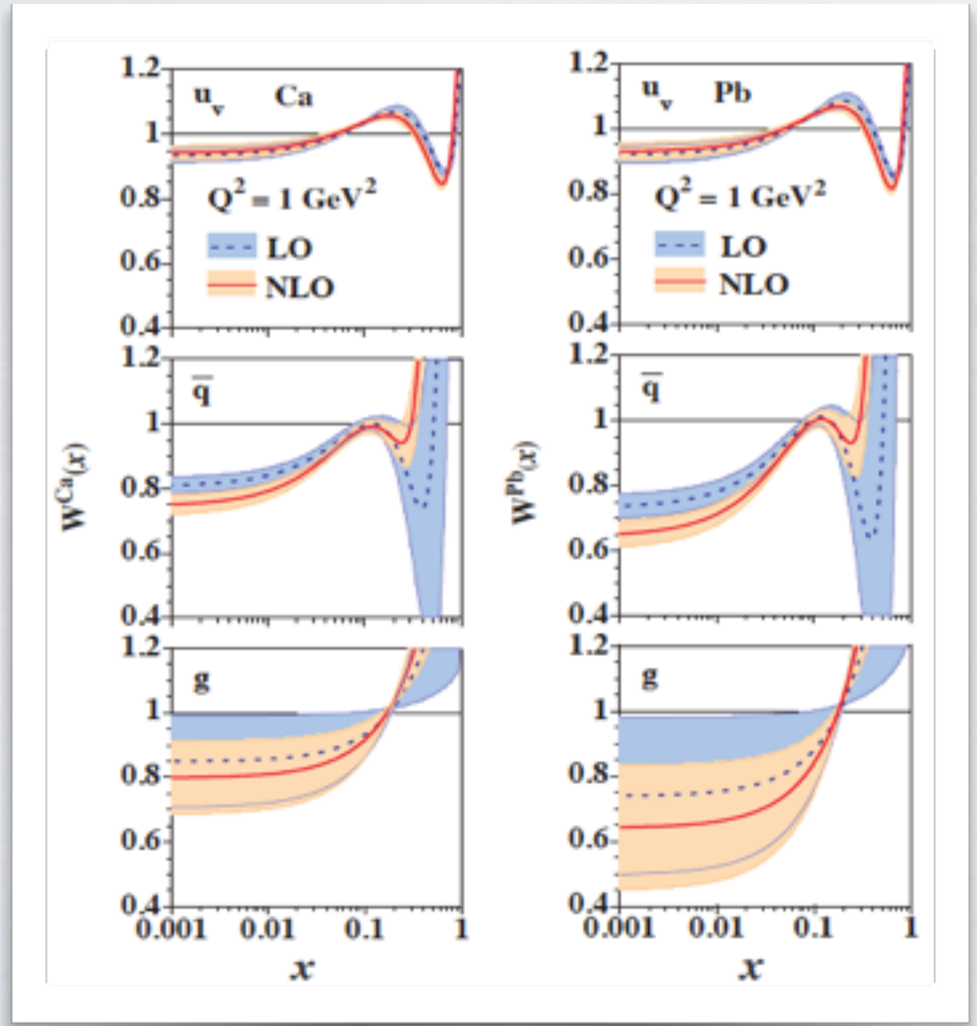

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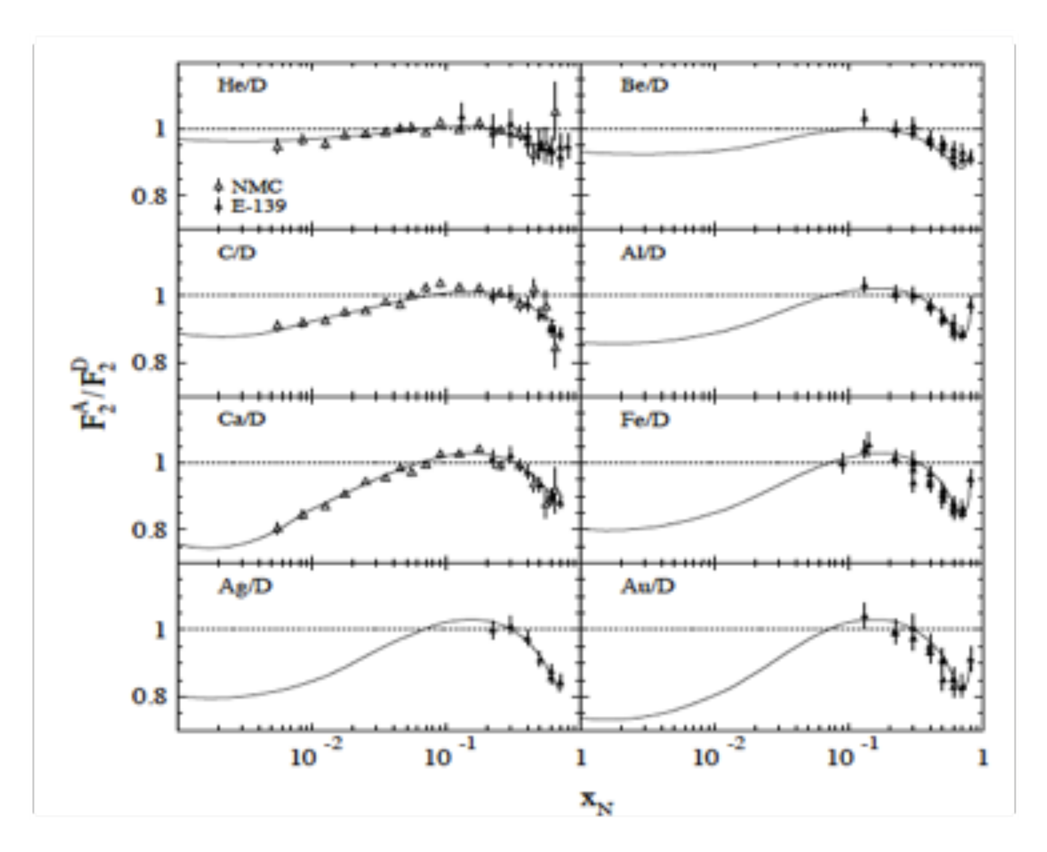

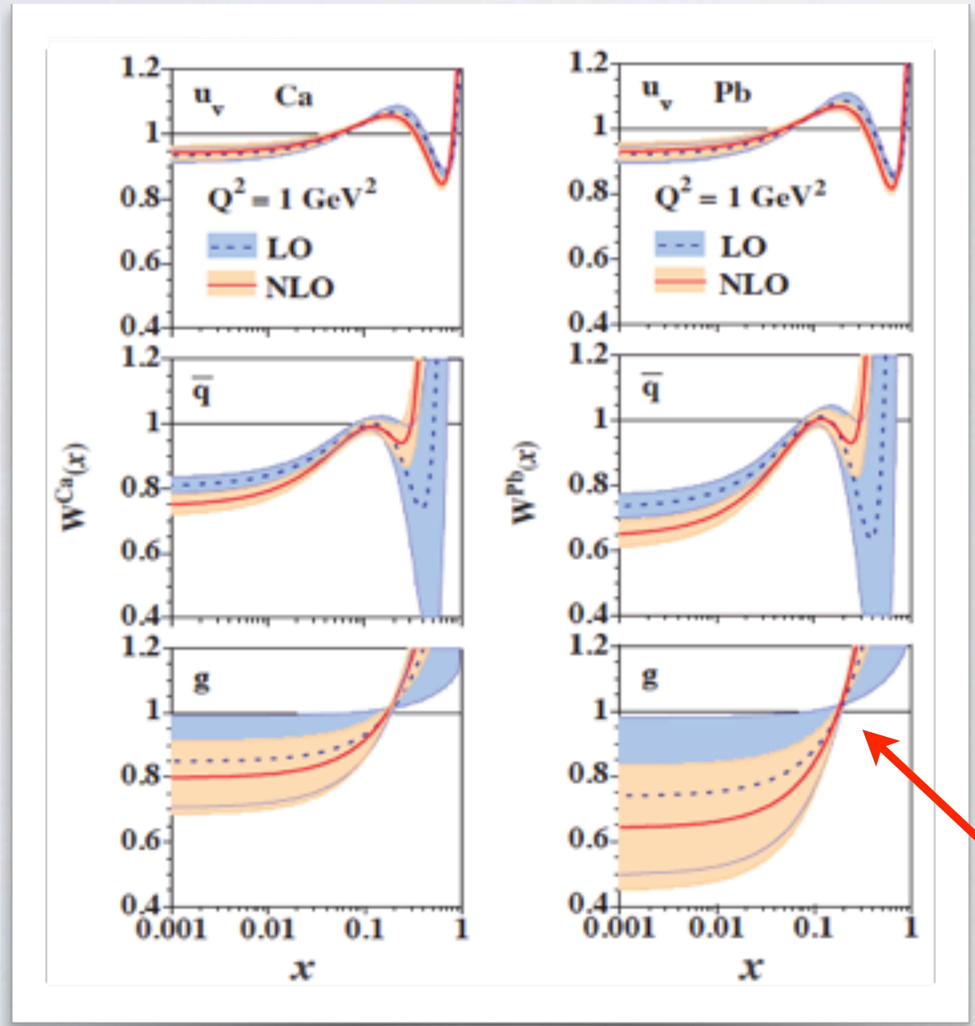

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- rather "unusual" gluon distribution at large x

selected nPDF fits (cont'd)

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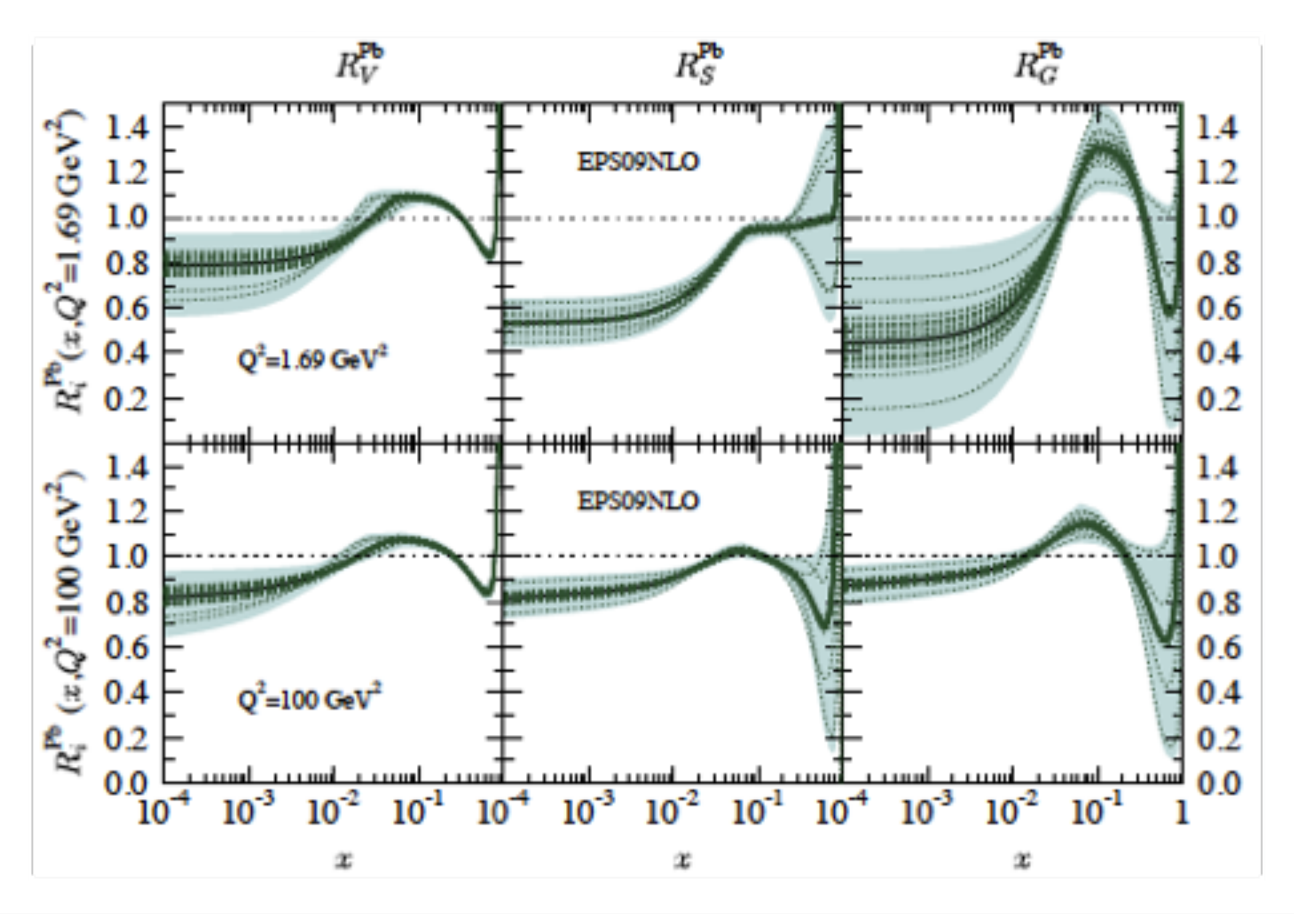

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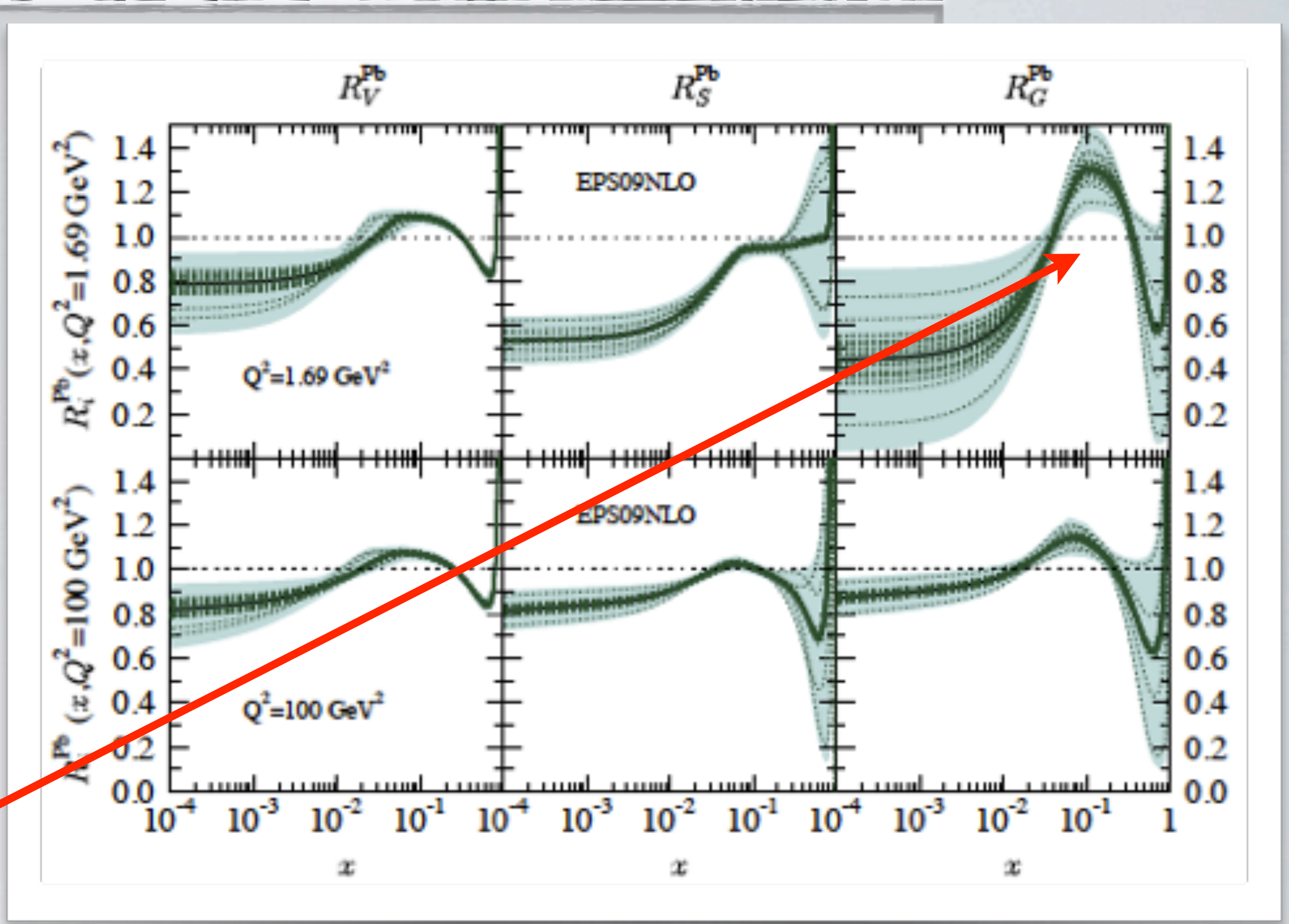

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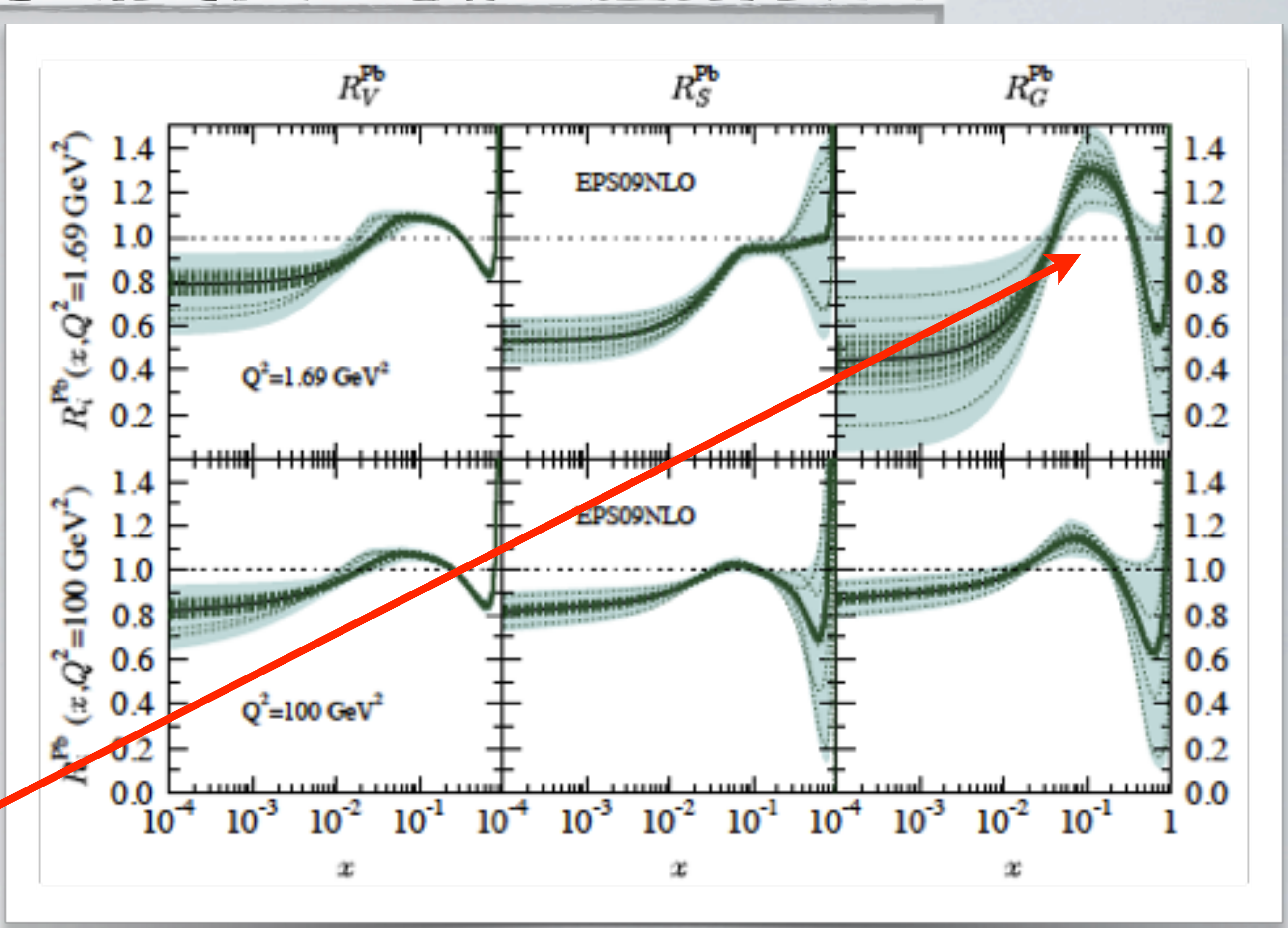

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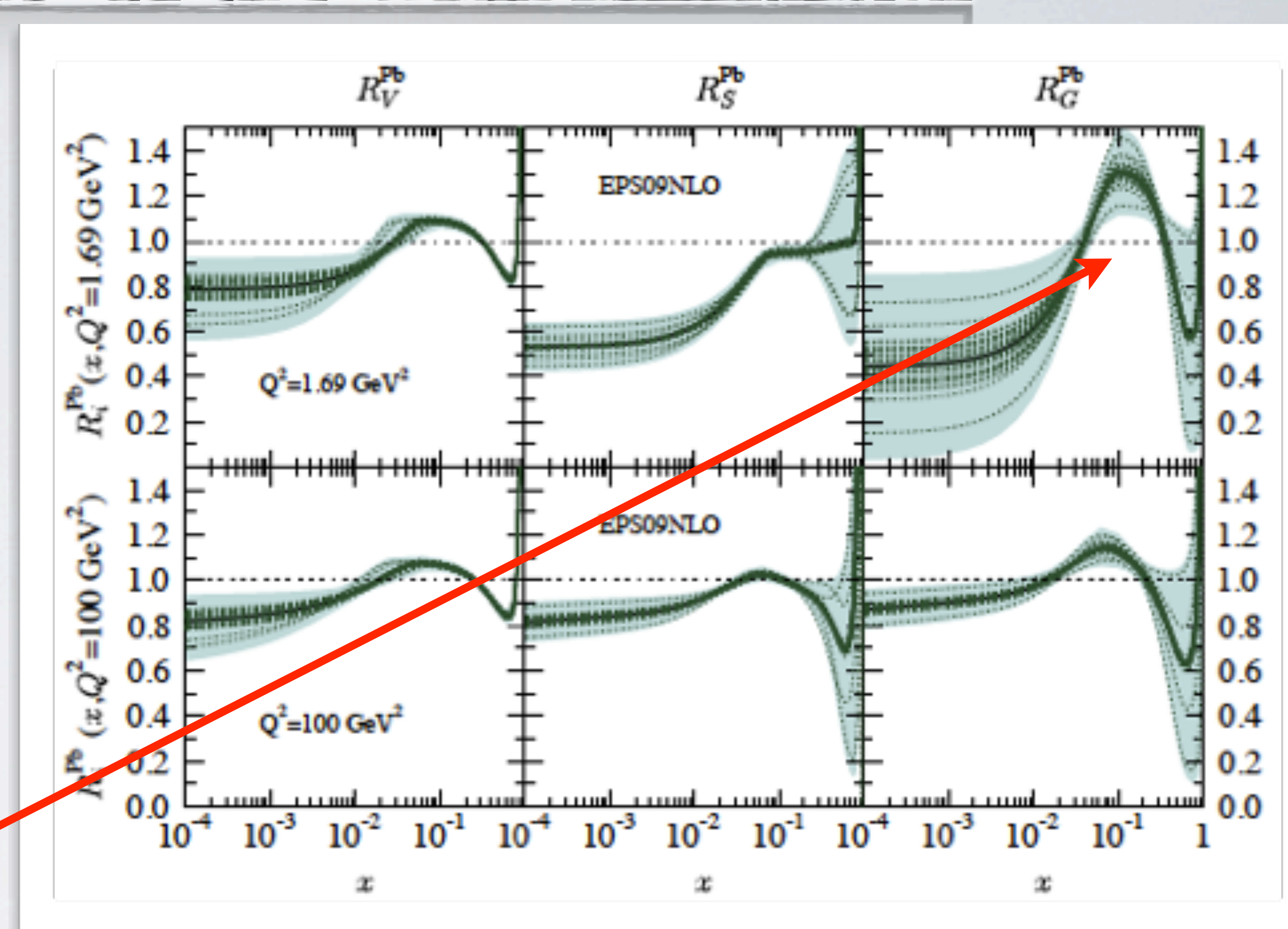

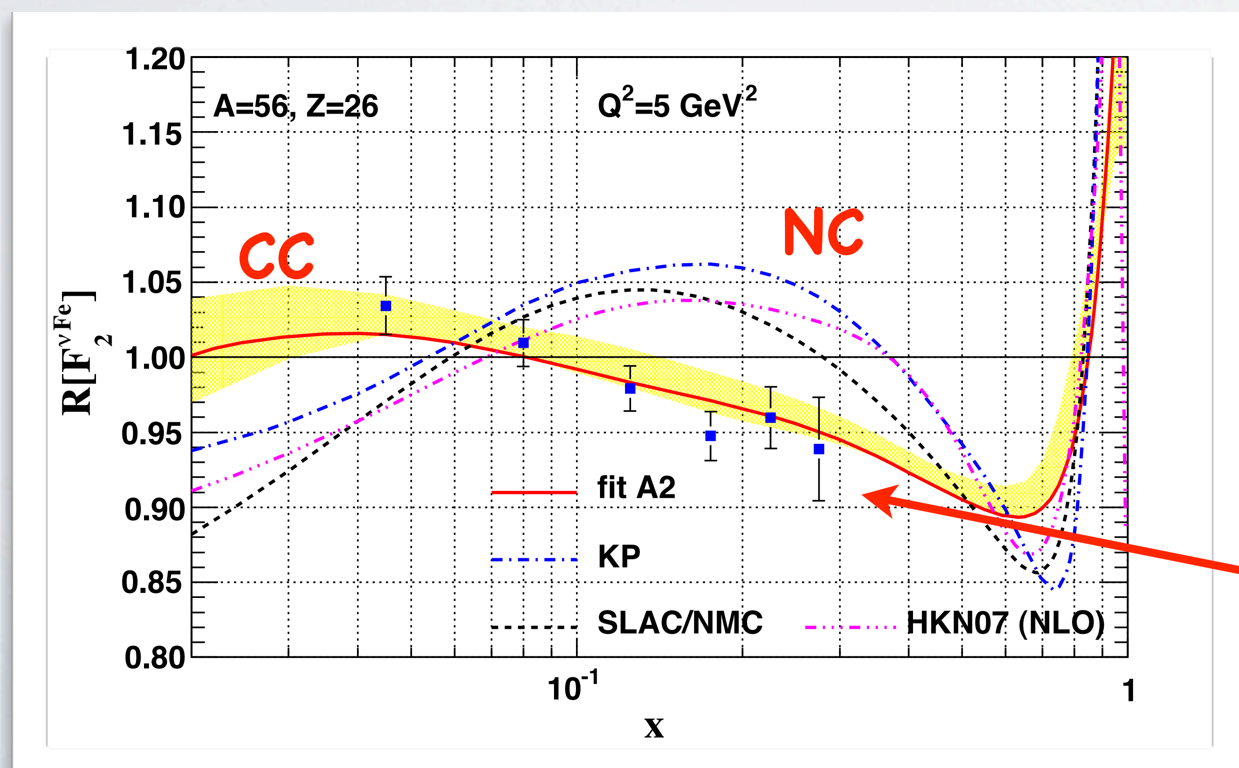

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- direct ansatz a la CTEQ
- DIS & DY plus **CC neutrino DIS data**
- find tension between NC and CC DIS data

breakdown of factorization

DSSZ global analysis

de Florian, Sassot, MS, Zurita - arXiv:1112.6324

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  - many different sets to choose from - take MSTW

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main questions to address

- do we really see a tension between charged lepton and neutrino DIS data
- do RHIC dAu data imply strong modifications of the nuclear gluon distribution

DSSZ global analysis - preliminaries

- use multiplicative nuclear modification factor $\mathbf{f_i^A(x, Q_0) = R_i^A(x, Q_0) \times f_i^p(x, Q_0)}$
- initial scale **Q_0 = 1 GeV**, NLO DGLAP evolution to all other scales $Q > Q_0$
- parametrize both valence distributions as

needs to be flexible enough to accommodate
(anti-)shadowing, EMC effect, Fermi motion

$$\mathbf{R_v^A(x, Q_0) = \epsilon_1\, x^{\alpha_v}(1-x)^{\beta_1} \times [1 + \epsilon_2(1-x)^{\beta_2}] \times [1 + a_v(1-x)^{\beta_3}]}$$

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$$\mathbf{R_s^A(x, Q_0) = R_v^A(x, Q_0) \, \frac{\epsilon_s}{\epsilon_1} \frac{1 + a_s x^{\alpha_s}}{a_s + 1}}$$

- need another modification factor for gluons

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total of 9 parameters per nucleus

$$\xi \in \{\alpha_v, \alpha_s, \alpha_g, \beta_1, \beta_2, \beta_3, a_v, a_s, a_g\}$$

parametrizing the A dependence

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- A dependence implemented as

$$\xi = \gamma_\xi + \lambda_\xi \mathbf{A}^{\delta_\xi}$$

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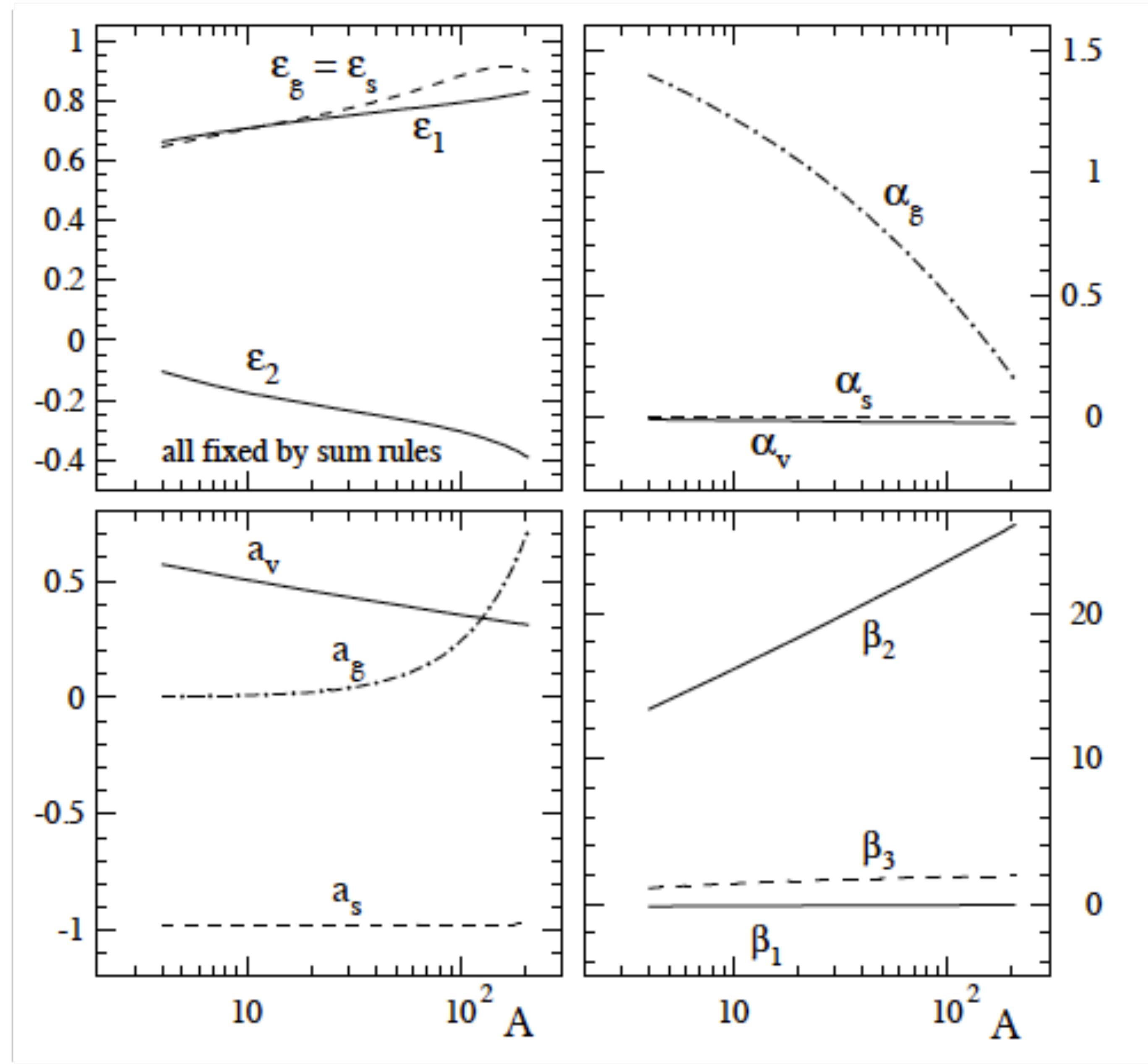
25 free parameters in total

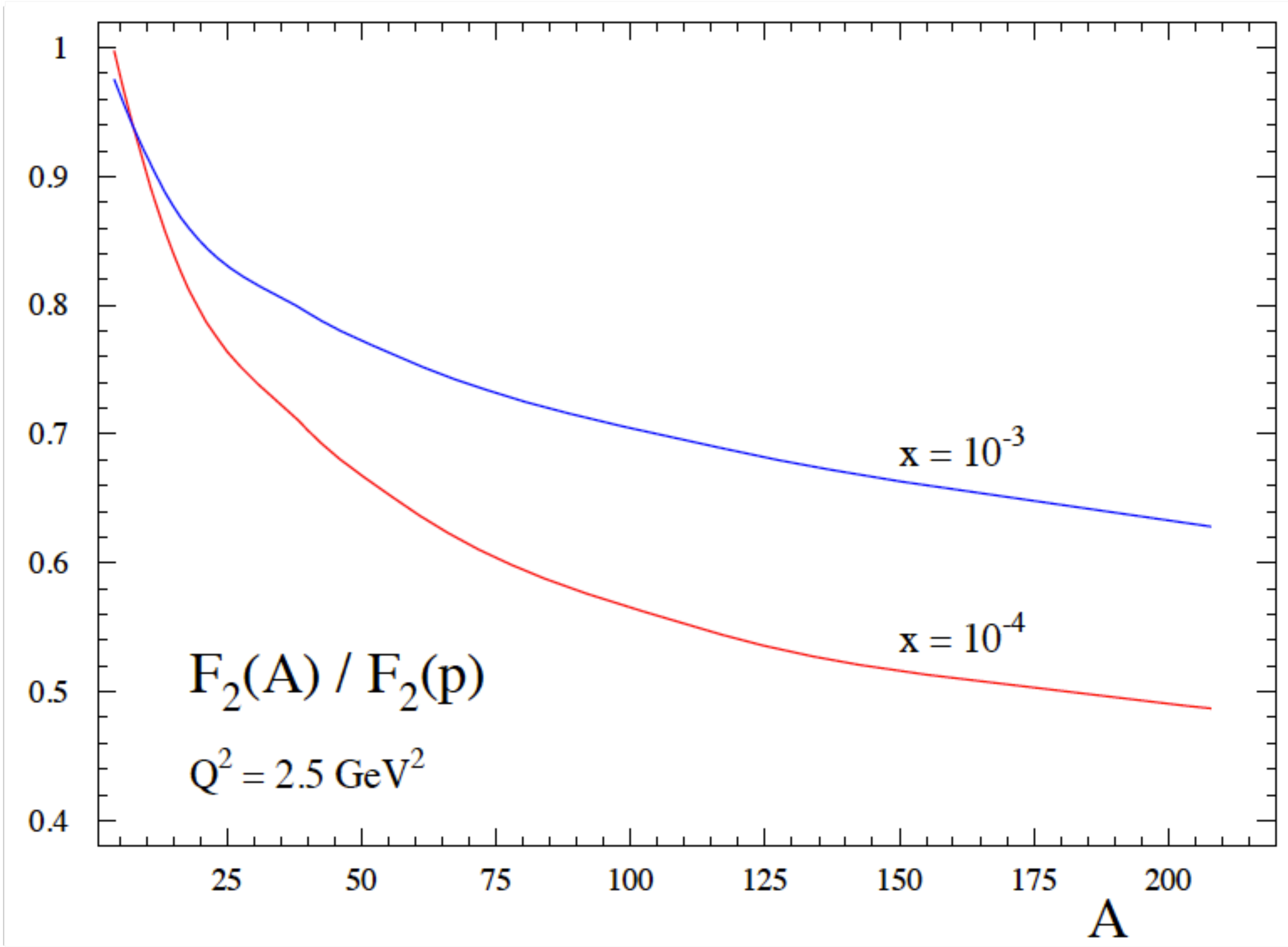
parameter	γ	λ	δ
α_v	-0.256	0.252	-0.017
α_s	0.001	-6.89×10^{-4}	0.286
α_g	1.994	-0.401	0.286
β_1	-5.564	5.36	0.0042
β_2	-59.62	69.01	0.0407
β_3	2.099	-1.878	-0.436
a_v	-0.622	1.302	-0.062
a_s	-0.980	2.33×10^{-6}	1.505
a_g	0.0018	2.35×10^{-4}	1.505

optimum NLO parameters at the input scale

A dependence of fit parameters



aside: A dependence of F_2^A/F_2^p @ eRHIC



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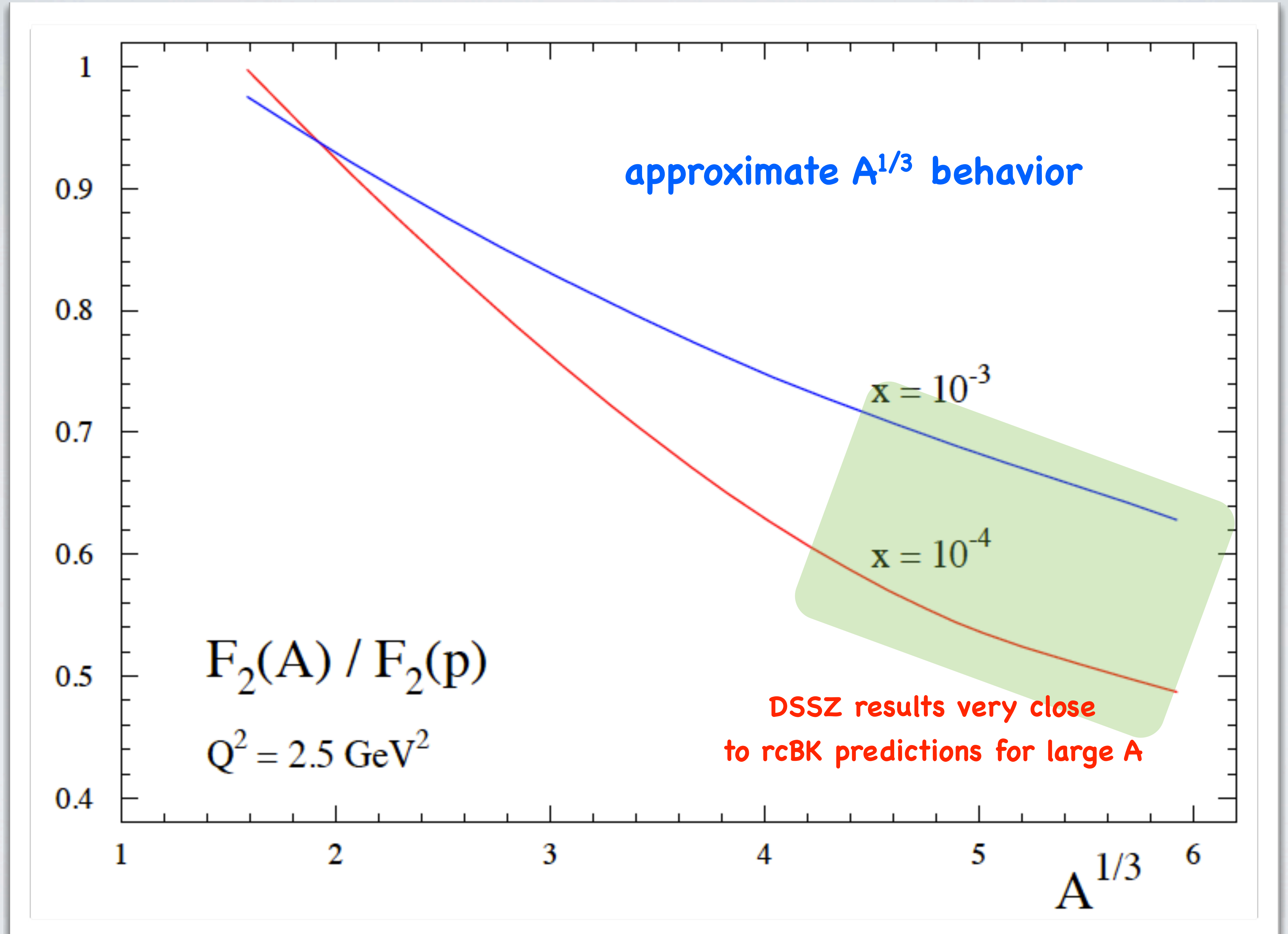

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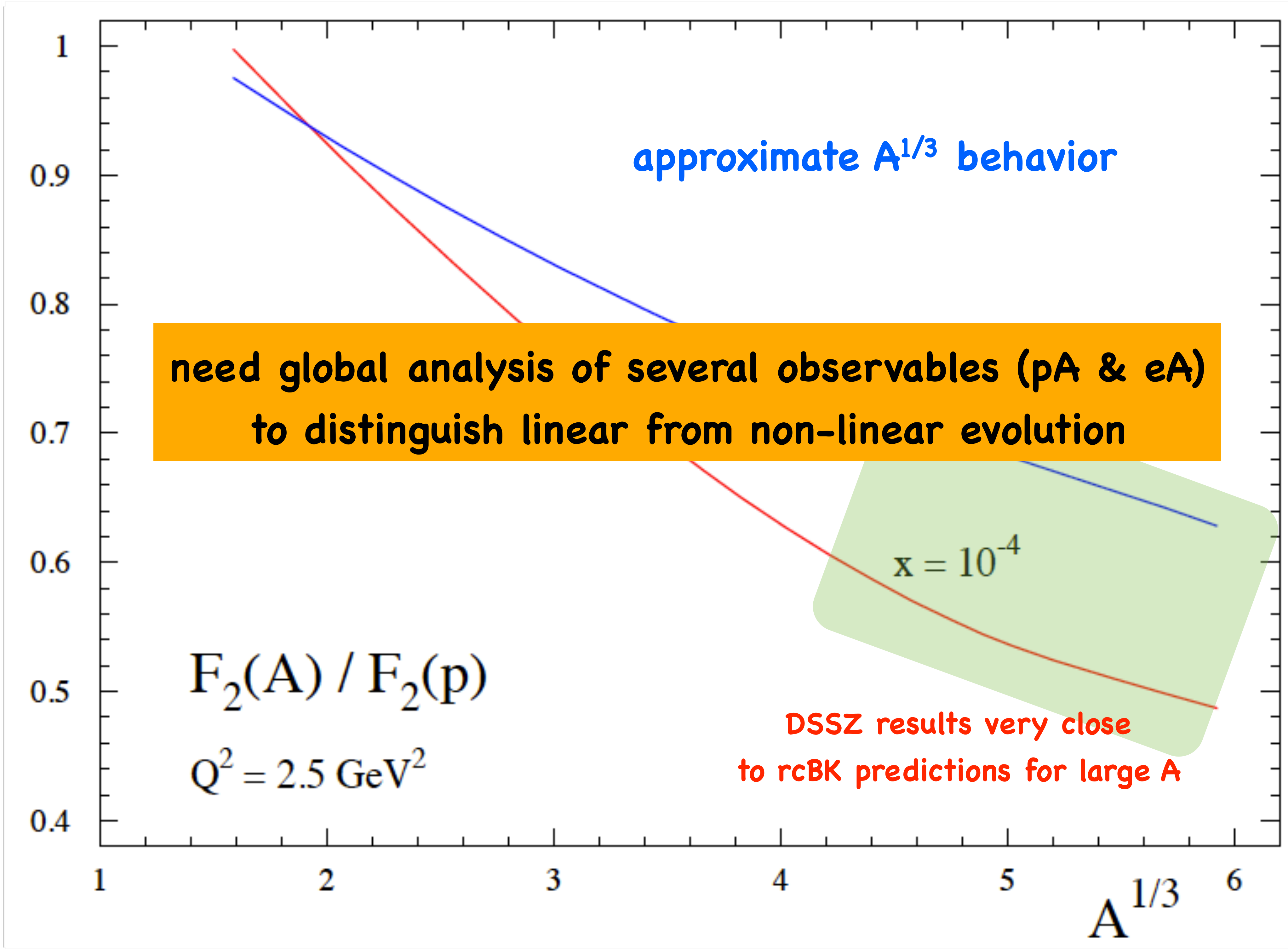


overall quality of the fit

- optimum parameters determined from standard chi-squared optimization

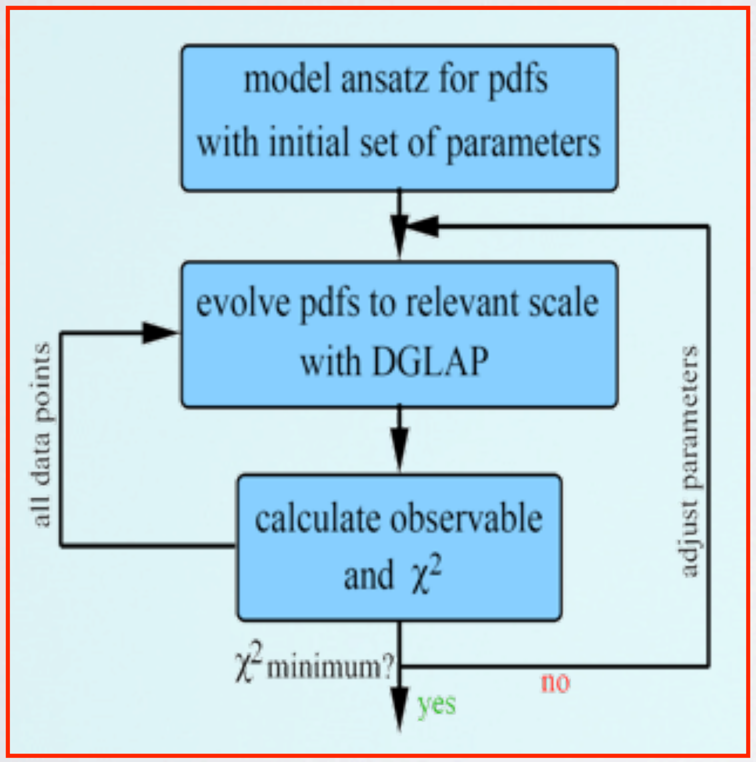
relative normalization or artificial weights for certain data sets

not needed/used in DSSZ analysis

$$\chi^2 \equiv \sum_i \omega_i \frac{(d\sigma_i^{\exp} - d\sigma_i^{th})^2}{\Delta_i^2}$$

uncertainty for each point

DSSZ: add sys + stat in quadrature [+ theor. unc.]



optimum set of parameters

total χ^2 : **1544.7/1579**pts.
χ^2/d.o.f : **0.994**

measurement	collaboration	# points	χ^2
F_2^{He}/F_2^D	NMC	17	18.18
	E139	18	2.71
F_2^{Li}/F_2^D	NMC	17	17.35
F_2^{Li}/F_2^D Q^2 dep.	NMC	179	197.36
F_2^{Be}/F_2^D	E139	17	44.17
F_2^C/F_2^D	NMC	17	27.85
	E139	7	9.66
	EMC	9	6.41
F_2^C/F_2^D Q^2 dep.	NMC	191	201.63
F_2^{Al}/F_2^D	E139	17	13.22
F_2^{Ca}/F_2^D	NMC	16	18.60
	E139	7	12.13
F_2^{Cu}/F_2^D	EMC	19	18.62
F_2^{Fe}/F_2^D	E139	23	34.95
F_2^{Ag}/F_2^D	E139	7	9.71
F_2^{Sn}/F_2^D	EMC	8	16.59
F_2^{Au}/F_2^D	E139	18	10.46
F_2^C/F_2^{Li}	NMC	24	33.17
F_2^{Ca}/F_2^{Li}	NMC	24	25.31
F_2^{Be}/F_2^C	NMC	15	11.76
F_2^{Al}/F_2^C	NMC	15	6.93
F_2^{Ca}/F_2^C	NMC	15	7.71
F_2^{Ca}/F_2^C	NMC	24	26.09
F_2^{Fe}/F_2^C	NMC	15	10.38
F_2^{Sn}/F_2^C	NMC	15	4.69
F_2^{Sn}/F_2^C Q^2 dep.	NMC	145	102.31
F_2^{Pb}/F_2^C	NMC	15	9.57
$F_2^{\nu Fe}$	NuTeV	78	109.65
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$F_2^{\nu Fe}$	CDHSW	120	108.20
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$d\sigma_{\pi^0}^{dAu}/d\sigma_{\pi^0}^{pp}$	STAR	11	3.92
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NC DIS **897.5/894**

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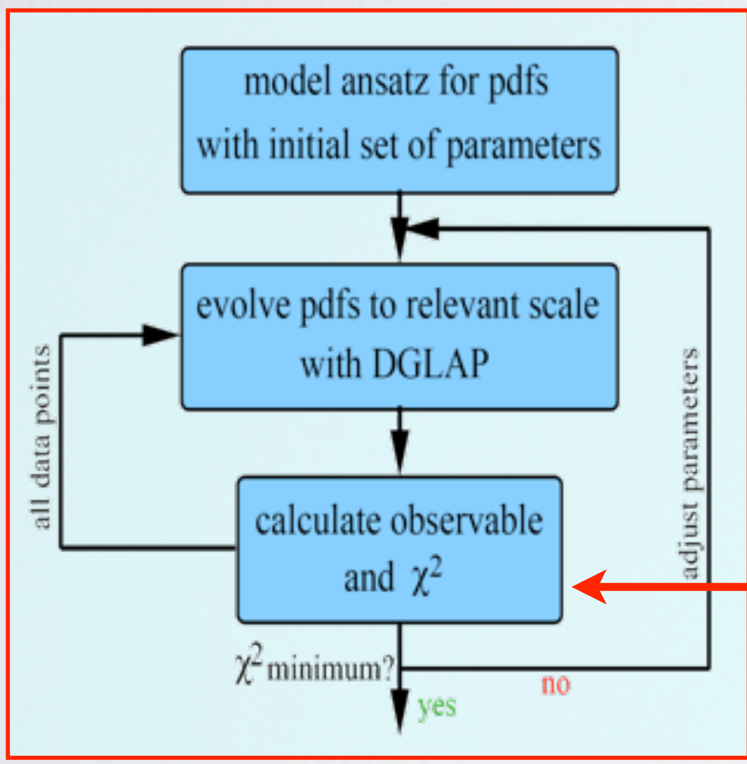

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NLO analysis: potential bottleneck

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technical aspects: Mellin technique

source of trouble: ubiquitous convolutions

$$\otimes: \quad \mathbf{g(x)} = \int_{\mathbf{x}}^{1} \frac{\mathbf{dy}}{\mathbf{y}}\, \mathbf{f(y)}\, \mathbf{P}(\frac{\mathbf{x}}{\mathbf{y}})$$

$$\mathbf{d}\sigma^{\mathbf{A}}_{\mathrm{DIS}} = \sum_{\mathbf{i}} \mathbf{f}^{\mathbf{A}}_{\mathbf{i}} \otimes \mathbf{d}\hat{\sigma}_{\mathbf{i}\gamma^* \to \mathbf{X}}$$

increasing level of painfulness

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"natural language" for pQCD calculations: **Mellin moments**

$$\phi(N) \equiv \int_0^1 dx\, x^{N-1}\, \phi(x)$$

integral transformation
complex Mellin N space

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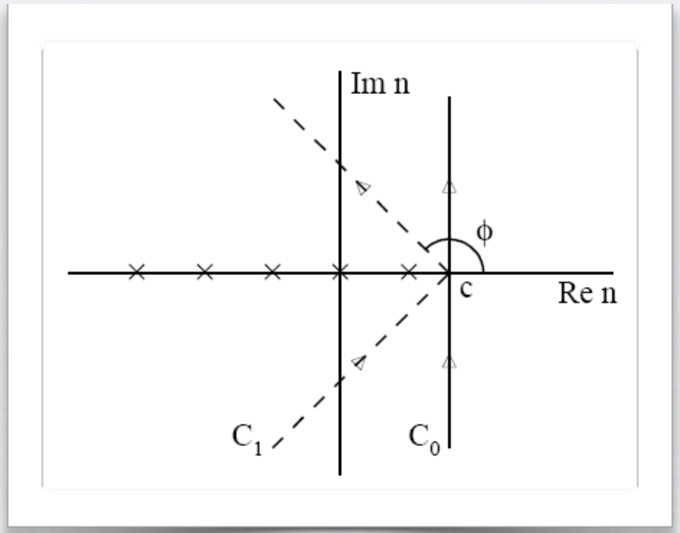

R.H. Mellin
Finnish mathematician
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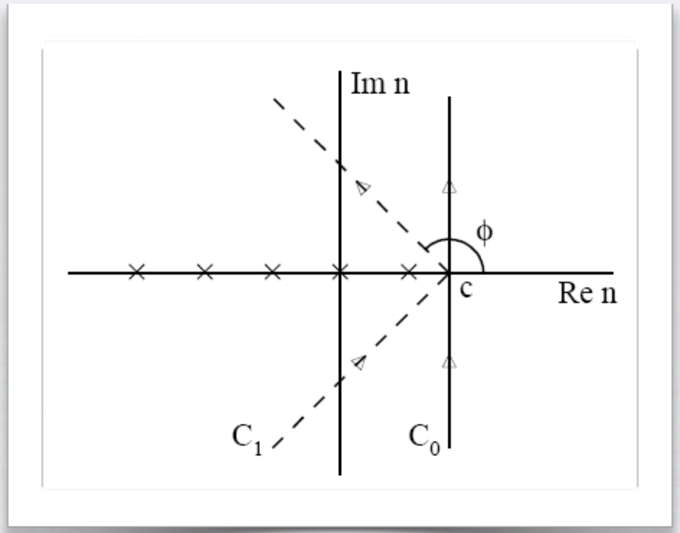

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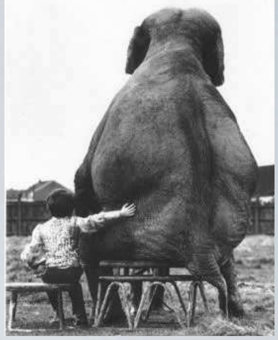
well-known property: convolutions factorize into simple products $\quad g(n) = f(n) \times P(n)$

- ✓ analytic solution to DGLAP evolution equations in Mellin space
- ✓ analytic expressions for DIS coefficient functions in Mellin space
- ✓ efficient numerical way to deal with complicated pp/pA cross sections

MS, Vogelsang – hep-ph/0108241

numerically very efficient
no K factor approximations needed

technical aspects: heavy flavors in CC DIS



charm production in CC DIS is of particular interest

idea: at LO $\mathbf{W^+ s' \to c}$ $\mathbf{s' \equiv |V_{cs}|^2 s + |V_{cd}|^2 d}$

- important to include charm mass through slow rescaling prescription $\xi = \mathbf{x(1 + m^2/Q^2)}$ Barnett '76
- prescription also needed for consistent factorization of collinear singularities in NLO Gottschalk '81

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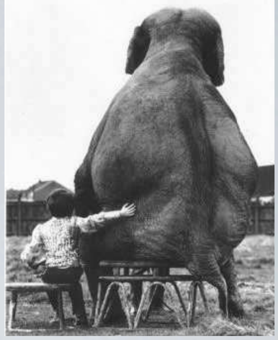

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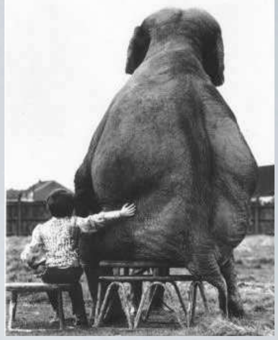

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complication: gluonic contributions in NLO Gottschalk '81; Gluck, Kretzer, Reya '96; Kretzer, MS '99

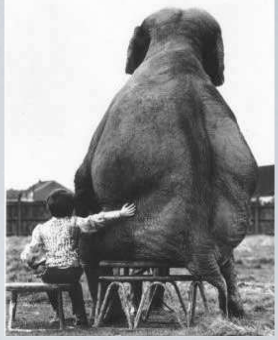
- dilute sensitivity to strangeness $\mathbf{W\,g \to c\,\bar{s}'}$
- keeping charm mass gets more complicated

$$\mathcal{F}_i^c(\mathbf{x}) = \mathbf{s}'(\xi) + \frac{\alpha_s}{2\pi} \int_\xi^1 \frac{d\zeta}{\zeta} \left[\mathbf{H}_i^{(1),q}(\zeta)\, \mathbf{s}'(\frac{\xi}{\zeta}) + \mathbf{H}_i^{(1),g}(\zeta)\, \mathbf{g}(\frac{\xi}{\zeta}) \right]$$

- make use of recently obtained expressions in Mellin space Blumlein, Hasselhuhn, Kovacikova, Moch

$$\mathcal{F}_i^c(\mathbf{N}) = \mathbf{s}'(\mathbf{N}) + \frac{\alpha_s}{2\pi} \left[\mathbf{H}_i^{(1),q}(\mathbf{N})\, \mathbf{s}'(\mathbf{N}) + \mathbf{H}_i^{(1),g}(\mathbf{N})\, \mathbf{g}(\mathbf{N}) \right]$$

technical aspects: heavy flavors in CC DIS



charm production in CC DIS is of particular interest

idea: at LO $\quad \mathbf{W^+ s' \to c} \quad \mathbf{s' \equiv |V_{cs}|^2 s + |V_{cd}|^2 d}$

- important to include charm mass through slow rescaling prescription $\xi = \mathbf{x(1 + m^2/Q^2)}$ Barnett '76
- prescription also needed for consistent factorization of collinear singularities in NLO Gottschalk '81

used to extract strangeness from CC neutrino data in proton PDF fits

need to control nuclear corrections for Fe and Pb targets

complication: gluonic contributions in NLO Gottschalk '81; Gluck, Kretzer, Reya '96; Kretzer, MS '99

- dilute sensitivity to strangeness $\mathbf{W\,g \to c\,\bar{s}'}$
- keeping charm mass gets more complicated

$$\mathcal{F}_i^c(x) = s'(\xi) + \frac{\alpha_s}{2\pi} \int_\xi^1 \frac{d\zeta}{\zeta} \left[H_i^{(1),q}(\zeta)\, s'(\frac{\xi}{\zeta}) + H_i^{(1),g}(\zeta)\, g(\frac{\xi}{\zeta}) \right]$$

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$$\mathcal{F}_i^c(N) = s'(N) + \frac{\alpha_s}{2\pi} \left[H_i^{(1),q}(N)\, s'(N) + H_i^{(1),g}(N)\, g(N) \right]$$

positive impact on quality of our fit to CC DIS data: 26% gain in χ^2

review of charged lepton DIS data

fit all “classic” EMC, NMC, and E-139 DIS data

- impose cut $\mathbf{Q^2 > 1\,\mathrm{GeV}^2}$
- $\chi^2 = \mathbf{857.5/894}\mathrm{pts.}$
- neglect, as usual, nuclear effects in deuterium
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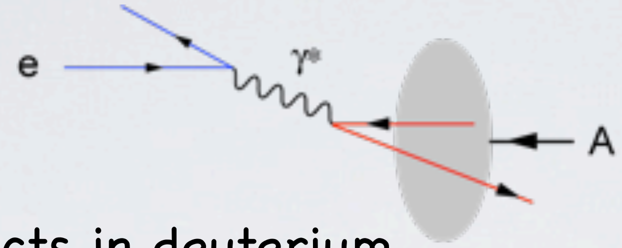

recall

main constraint from DIS data $\quad 0.01 \lesssim x \lesssim 0.8$

$$\mathbf{F_2^A(N) = x\sum_q e_q^2\Big[(q^A(N) + \bar{q}^A(N))(1 + \frac{\alpha_s}{2\pi}C_2^q(N))}$$
$$\mathbf{+\frac{\alpha_s}{2\pi}C_2^g(N)g^A(N)\Big]}$$

weak indirect constraint from scale evolution

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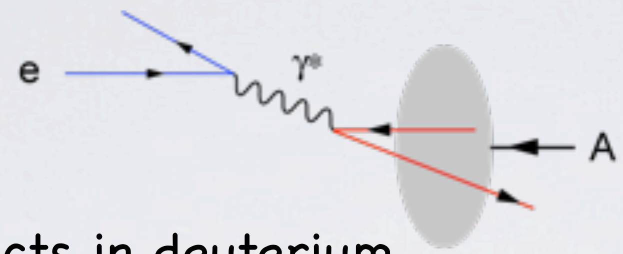

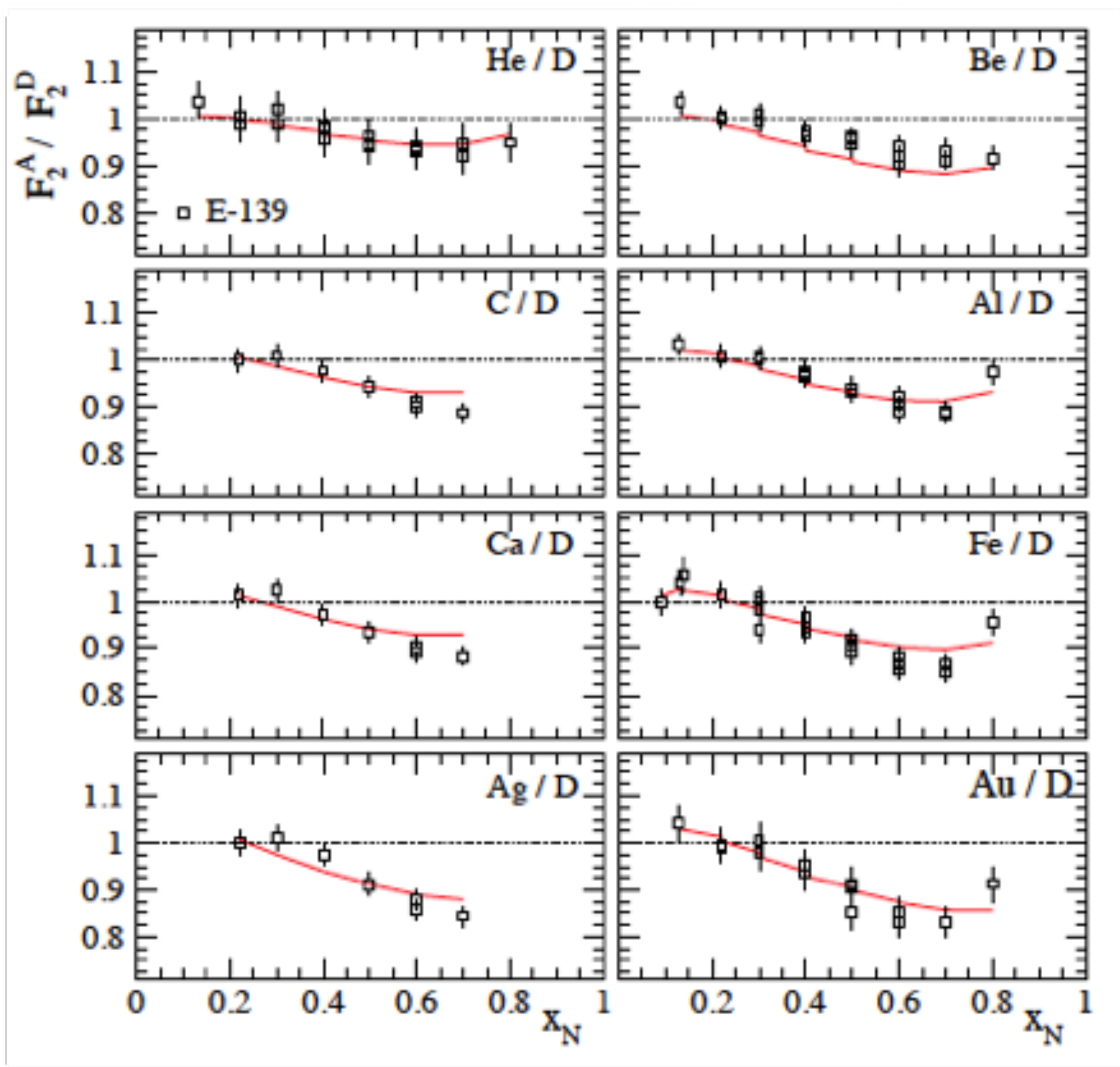

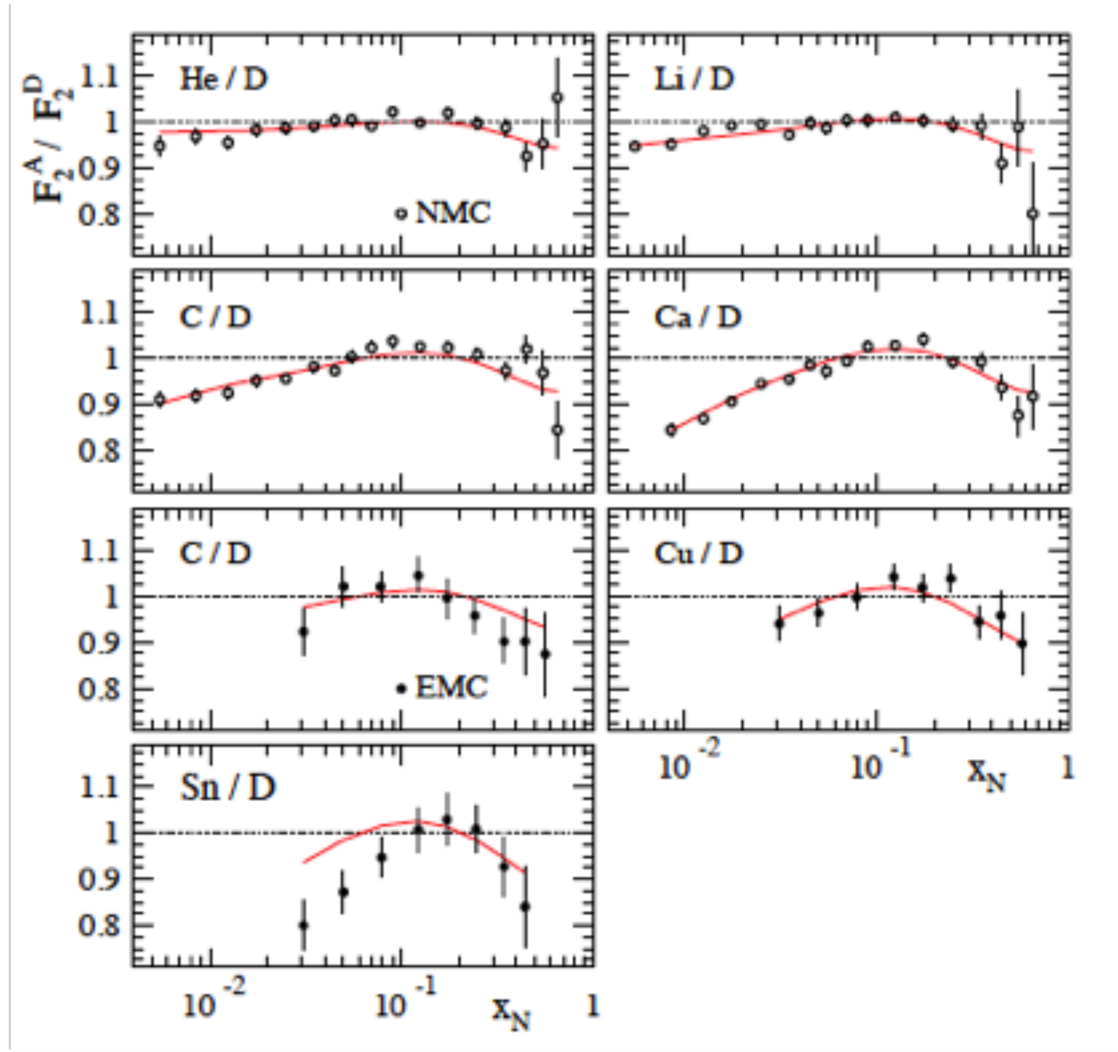

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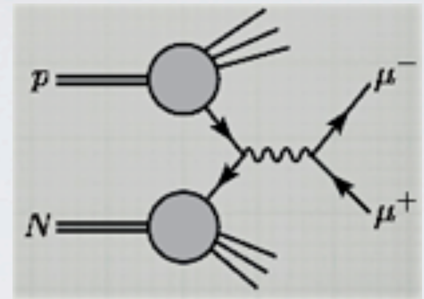
weak indirect constraint from scale evolution

Drell Yan di-muon data

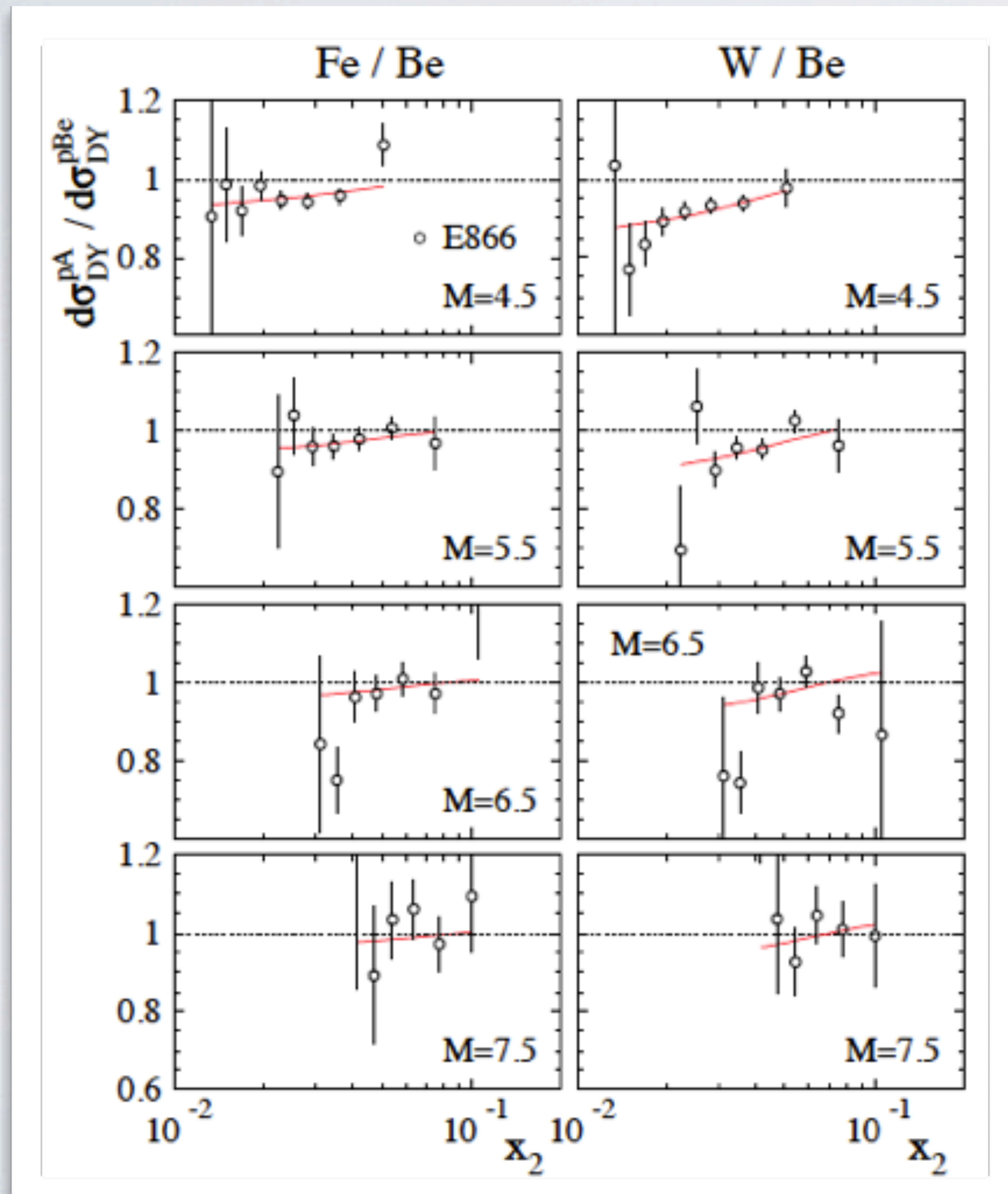
fit all E772 and E866 DY pA data

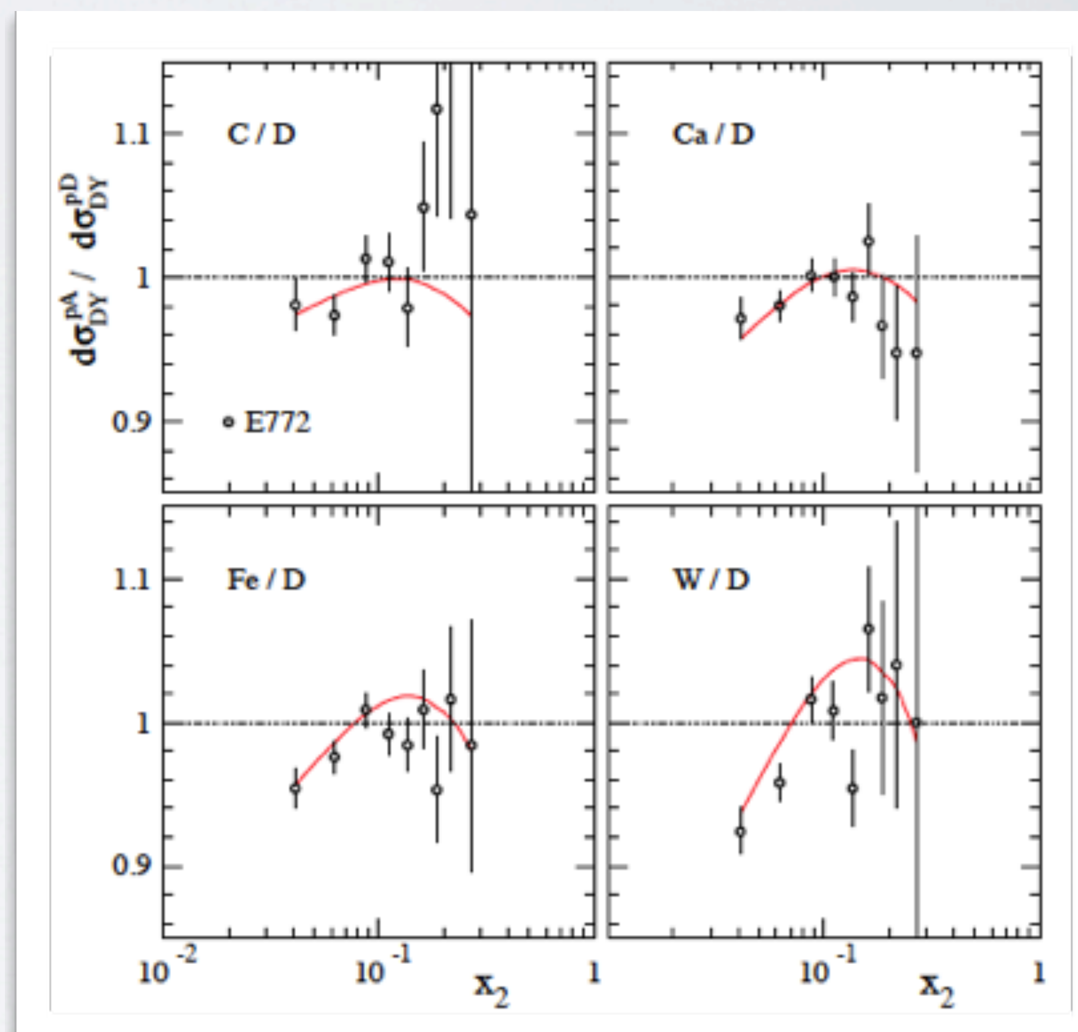
- di-muons have inv. mass M > 4 GeV (sets scale)
- $\chi^2 = \mathbf{90.7/92}\text{pts.}$



$$\mathbf{x_{1,2}} = \sqrt{\mathbf{M^2/s}}\,\mathbf{e^{\pm y}}$$

$$\frac{\mathbf{d^2}\sigma}{\mathbf{dMdy}} = \frac{\mathbf{4}\pi\alpha^{\mathbf{2}}}{\mathbf{9M^3}} \sum_{\mathbf{ij}} \int \mathbf{dx_1 dx_2\, f_i^P(x_1)\, f_j^A(x_2)}\, \frac{\mathbf{d}\hat{\sigma}_{\mathbf{ij}}}{\mathbf{dMdy}}$$





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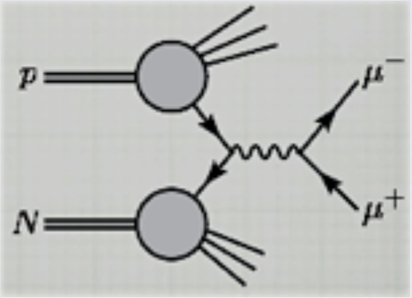

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DY data mainly help to disentangle val/sea quarks

gluons through evolution

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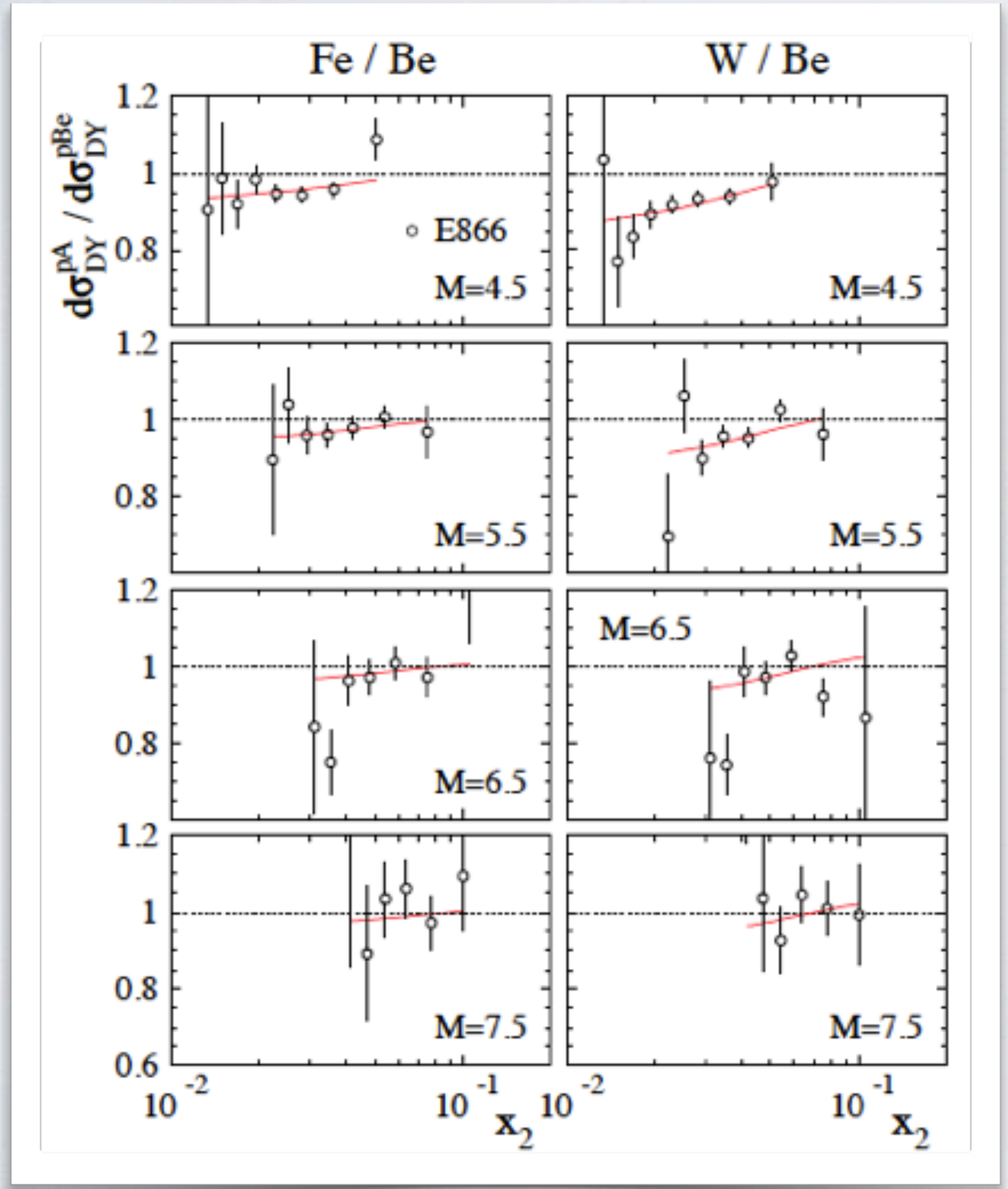

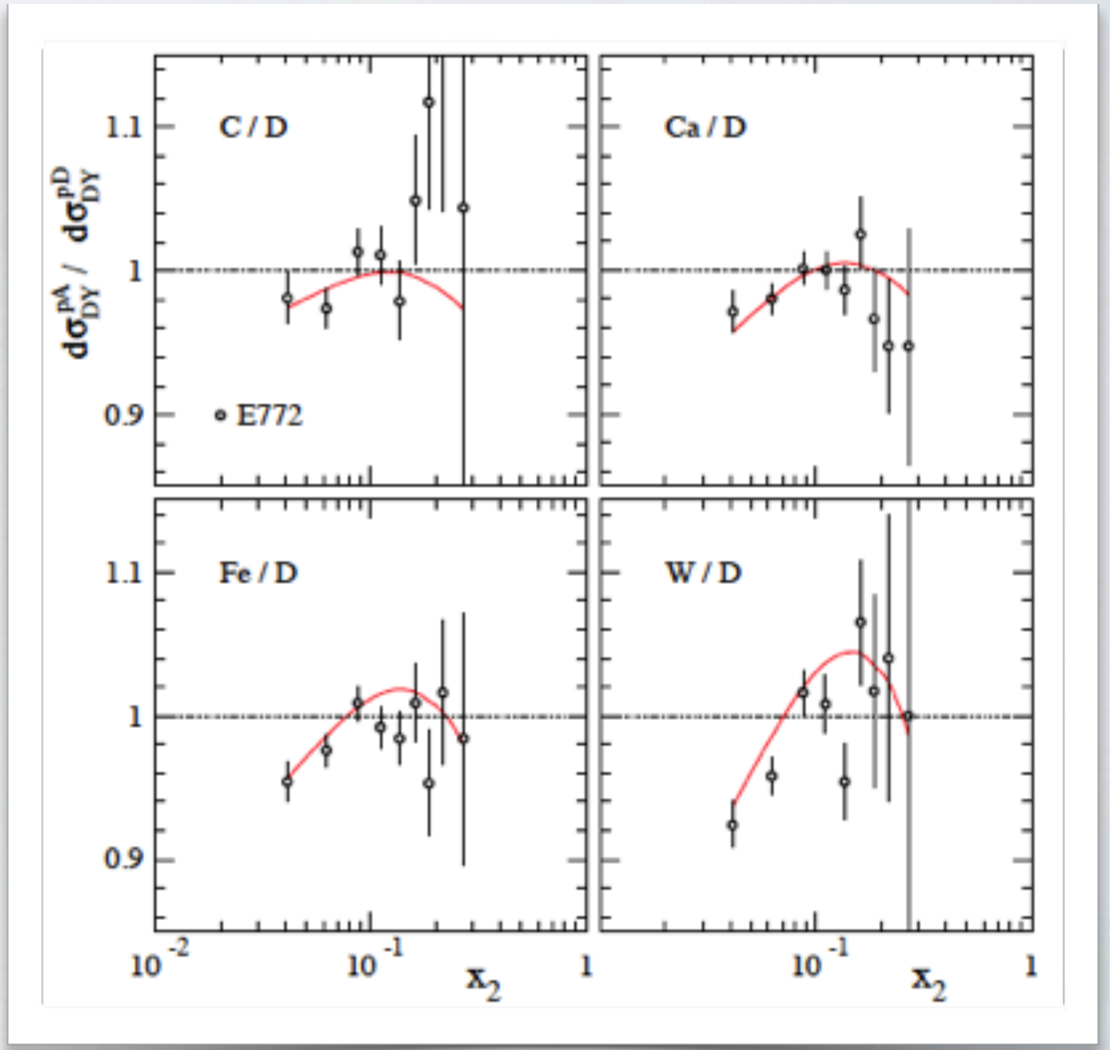

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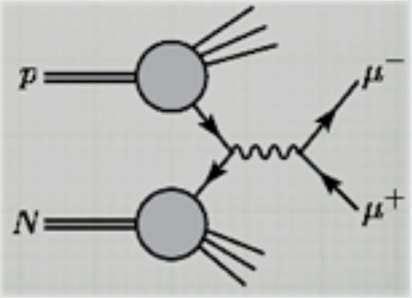

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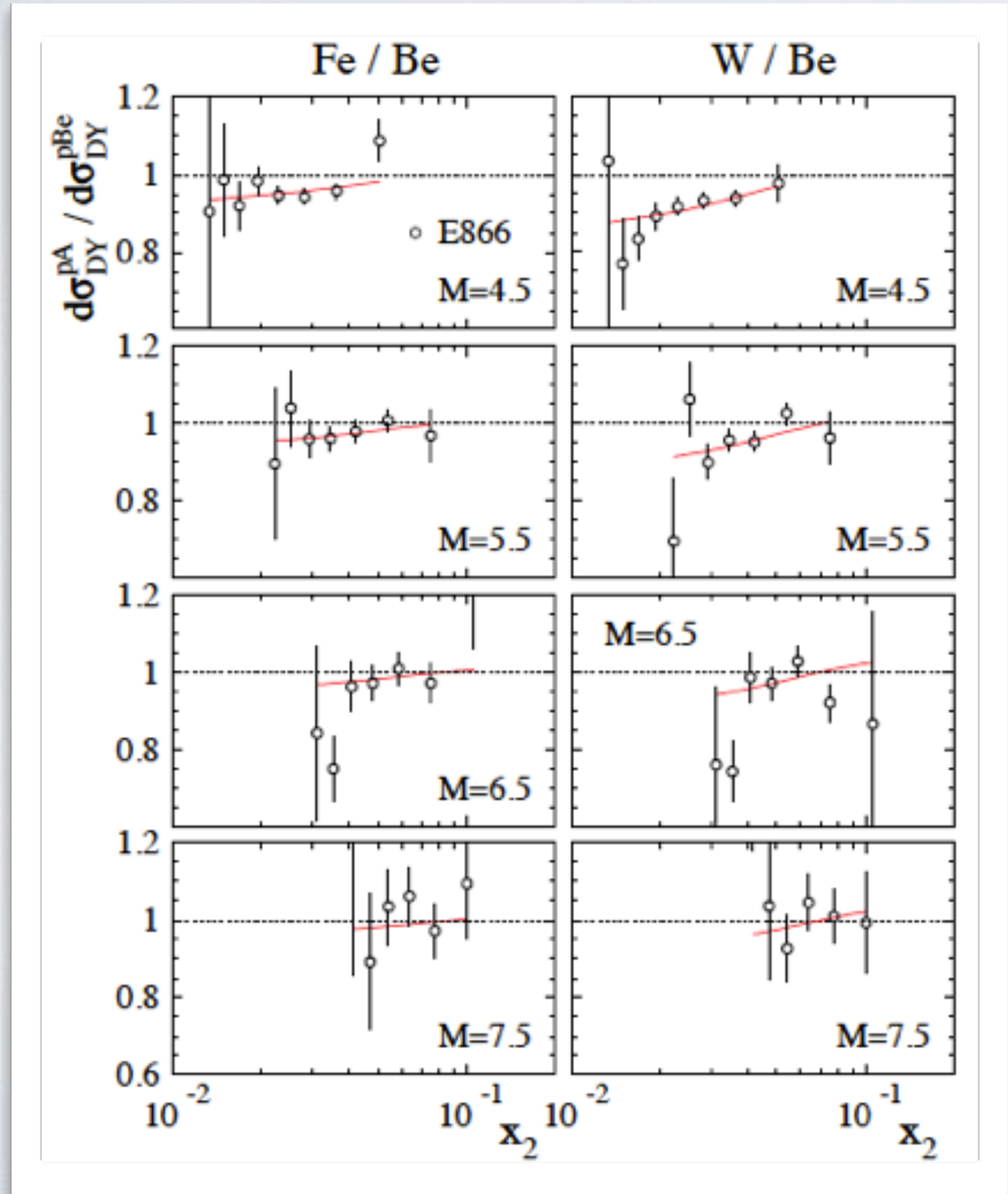
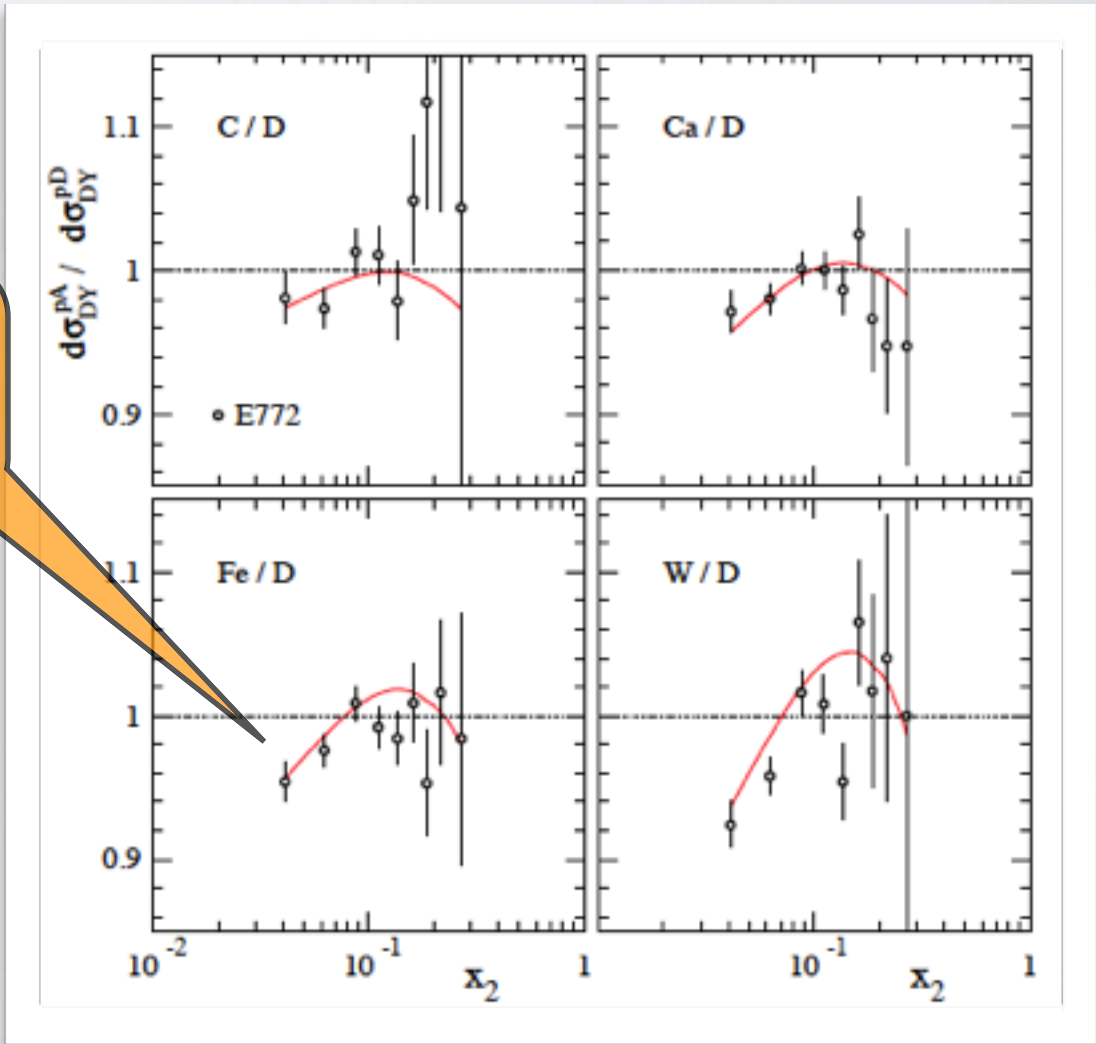


"evidence" for shadowing of sea quarks

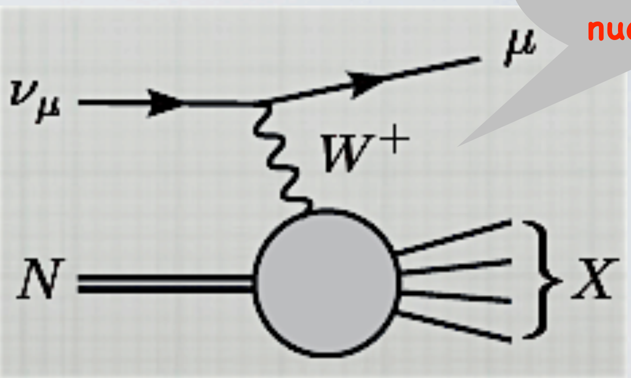


CC neutrino DIS data

fit CDHSW, NuTeV, and CHORUS str. fct. data

substantial interest:

- nCTEQ claim of "**factorization breaking**" for nPDFs
- neutrino data are a vital constraint on strangeness (and help to separate quark flavors) in proton PDF fits



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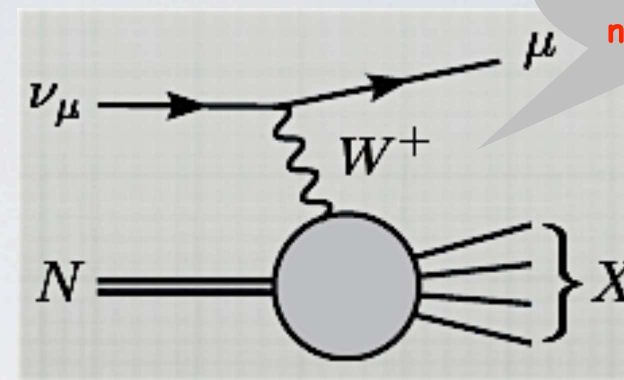
does a W interact differently with nuclear matter?



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here is how the "tension" story goes

- CC DIS data probe different combinations of up-/down-type quarks than charged-lepton DIS
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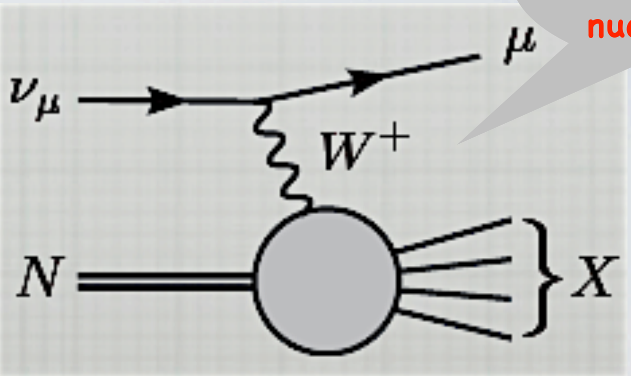

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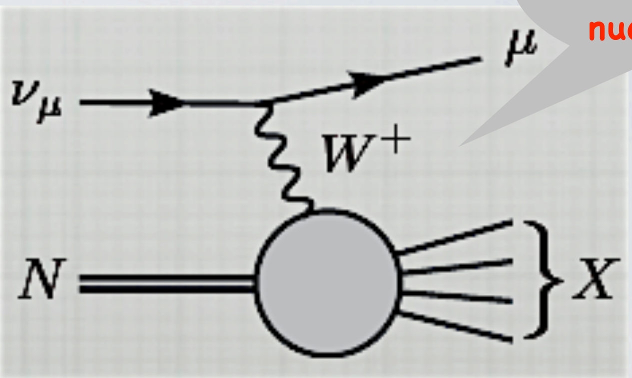

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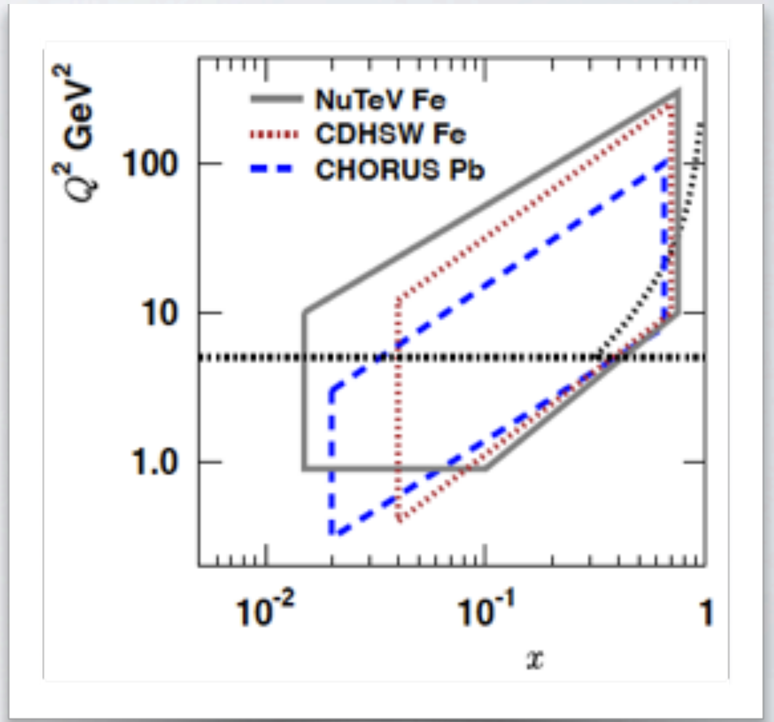

kinematics overlaps with charged lepton DIS data

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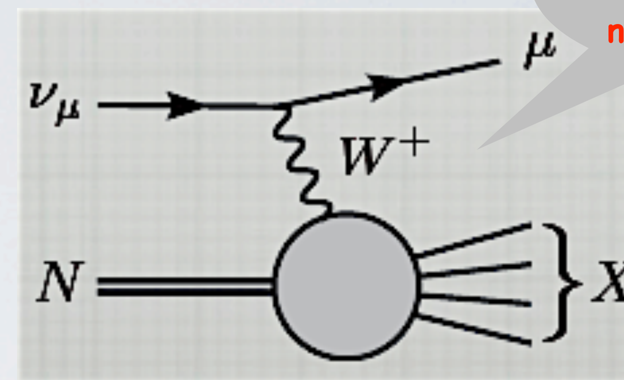

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potential tension with what we have learned from NC DIS

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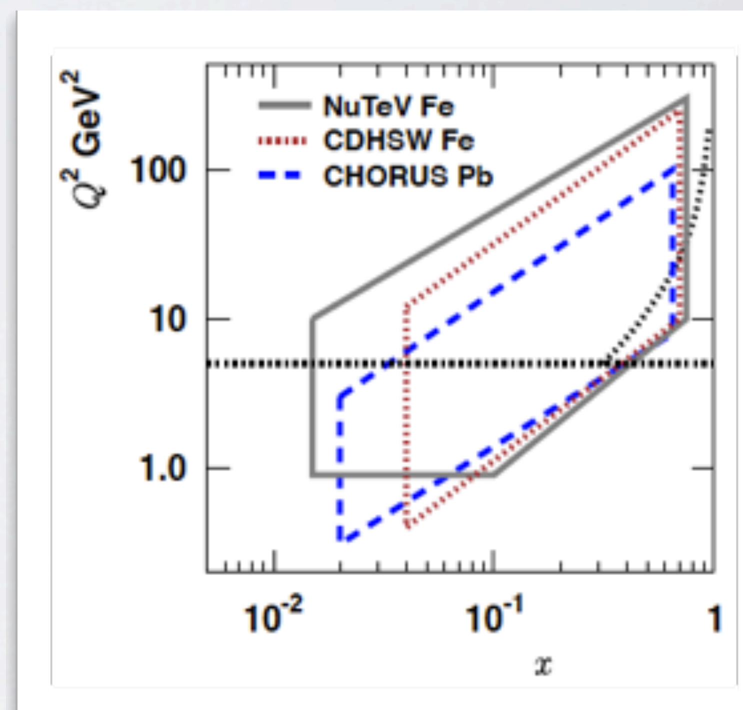

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CC neutrino DIS data (cont'd)

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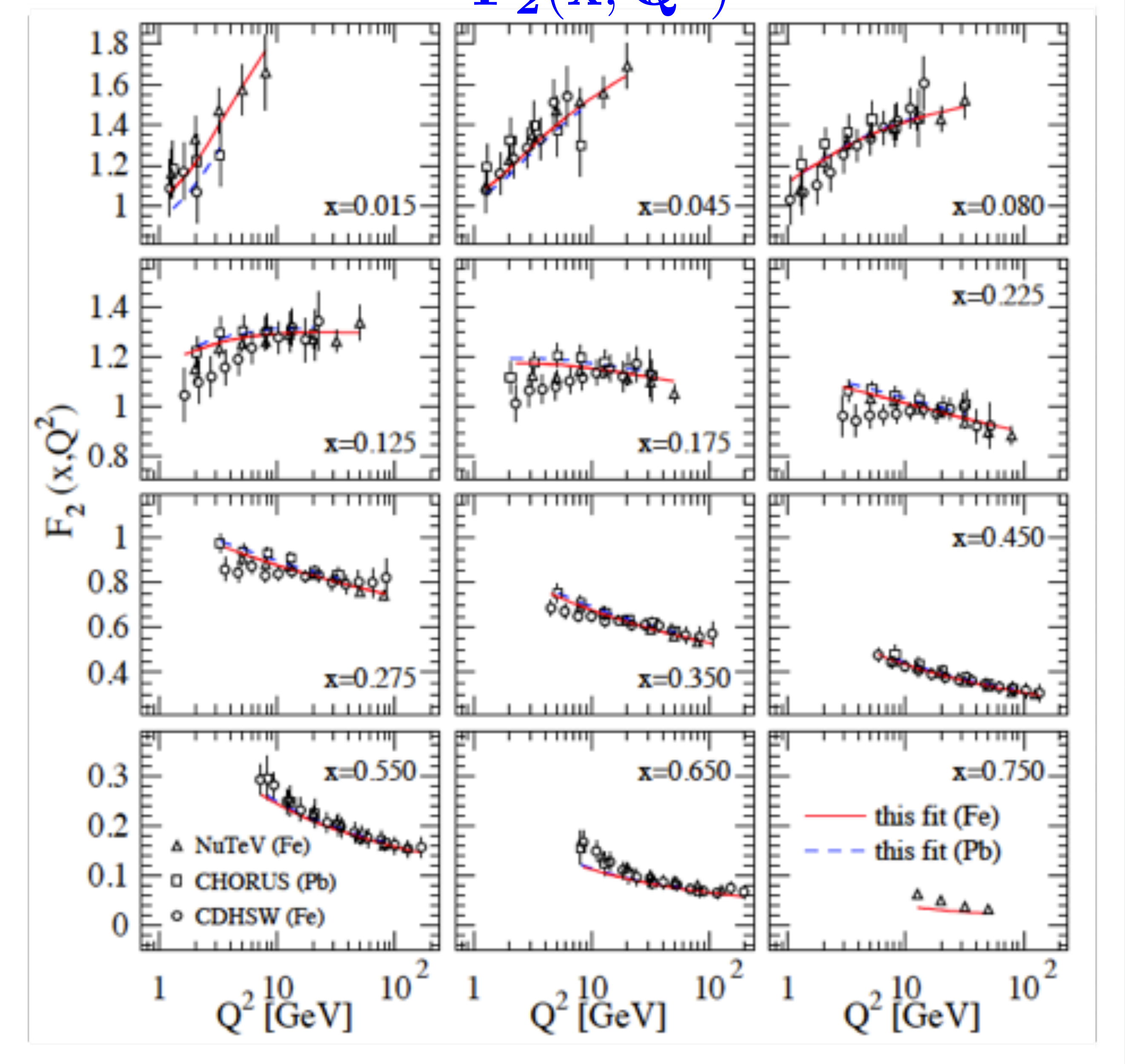
$\mathbf{F_2(x, Q^2)}$



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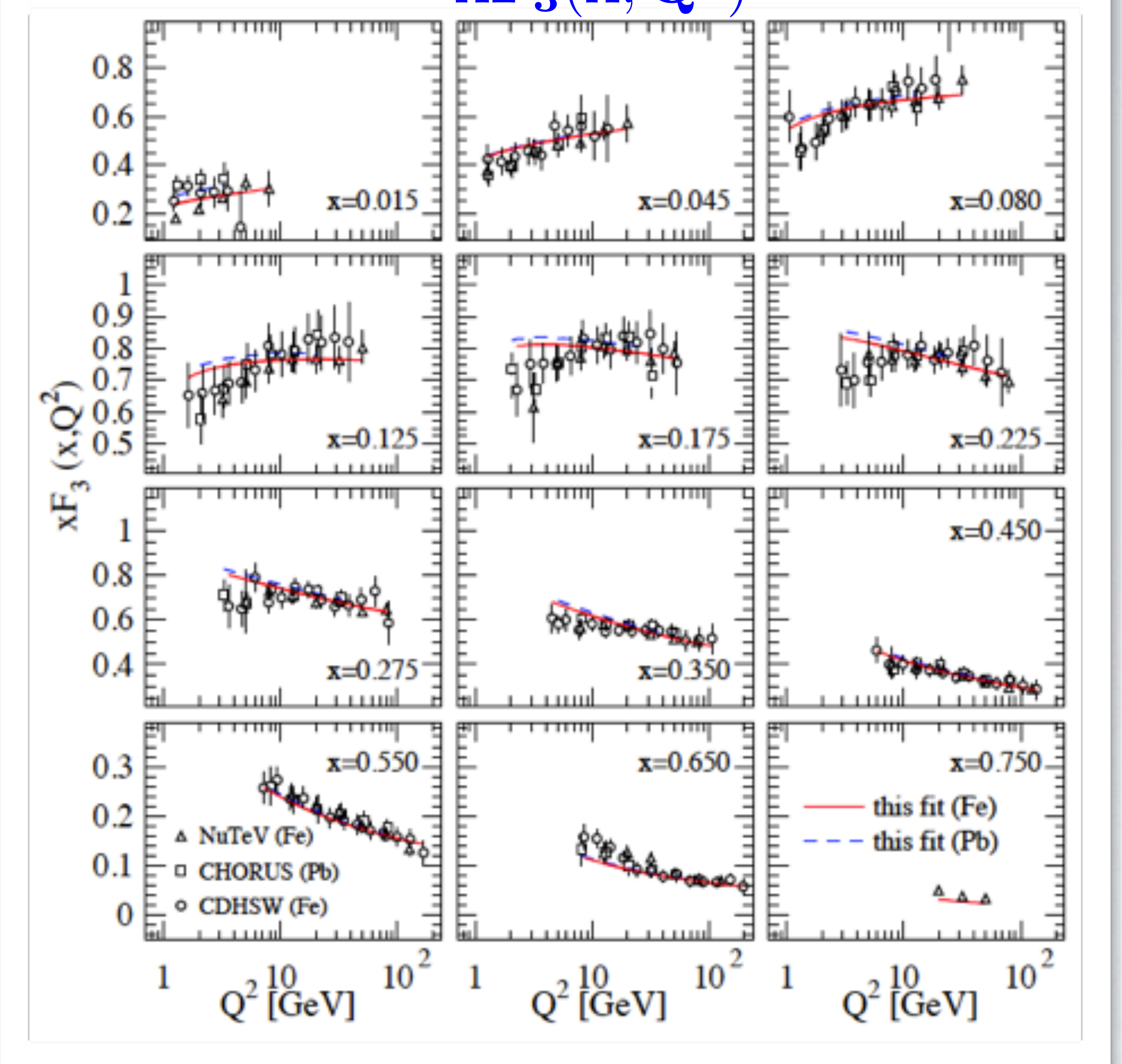

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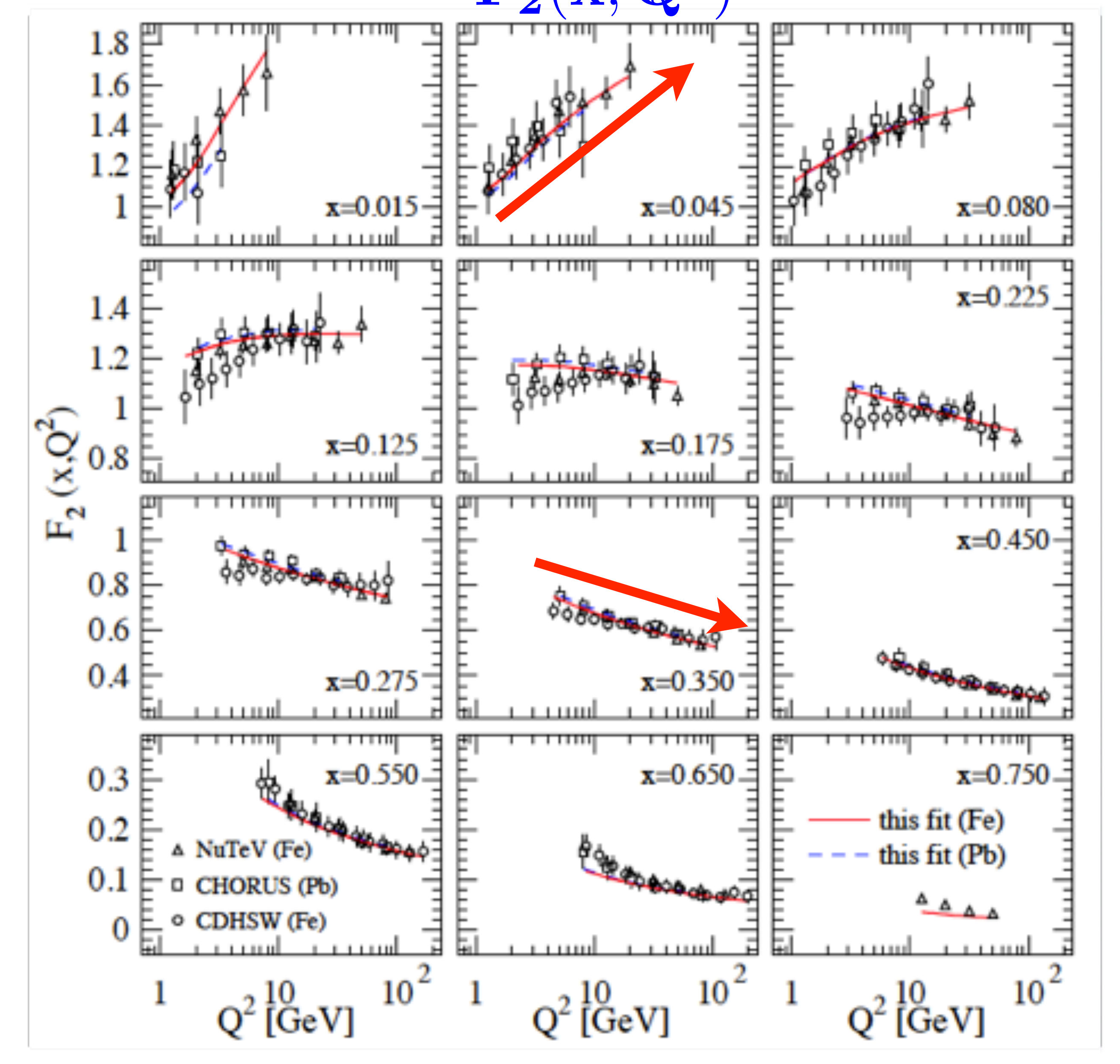

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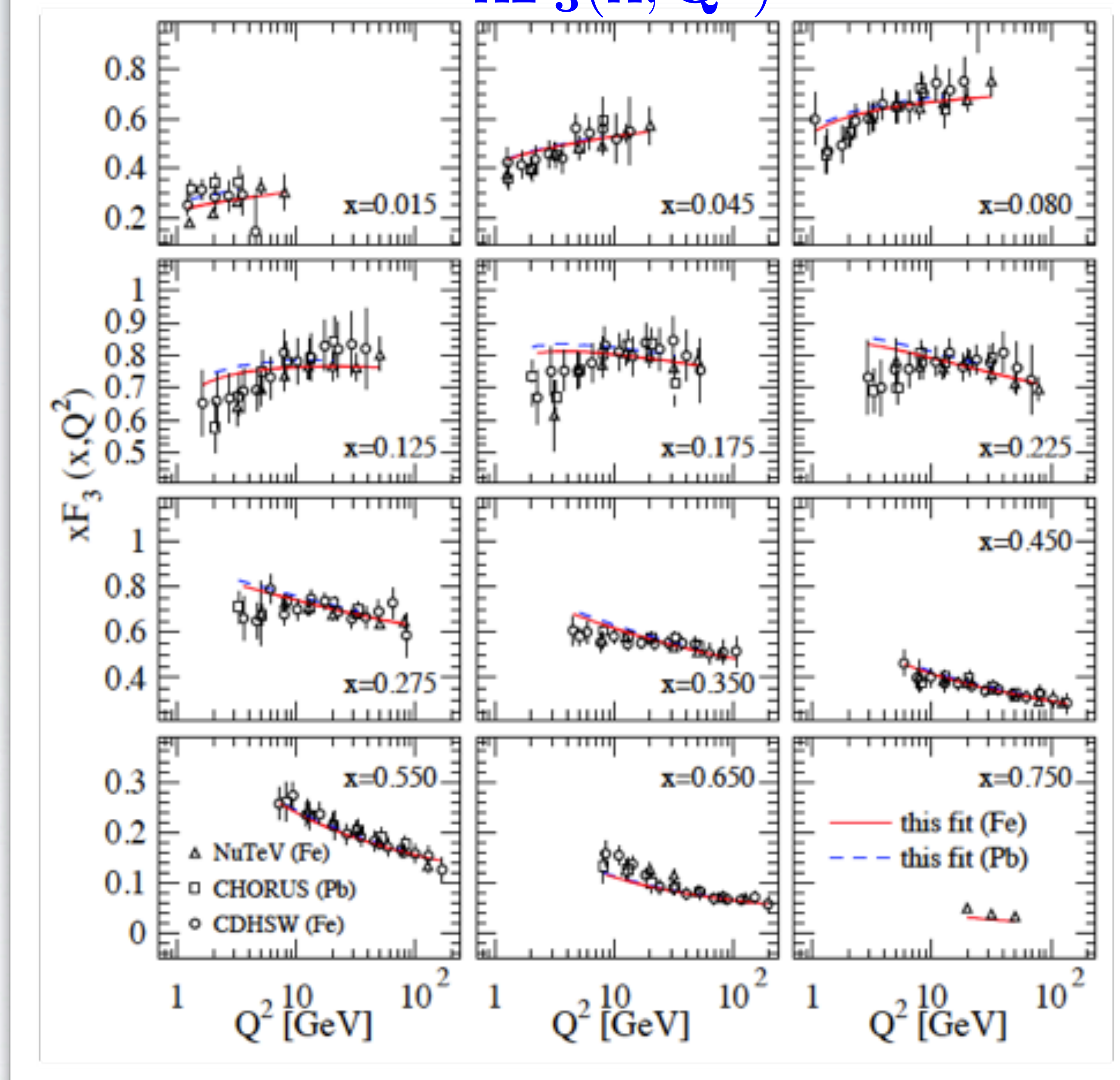

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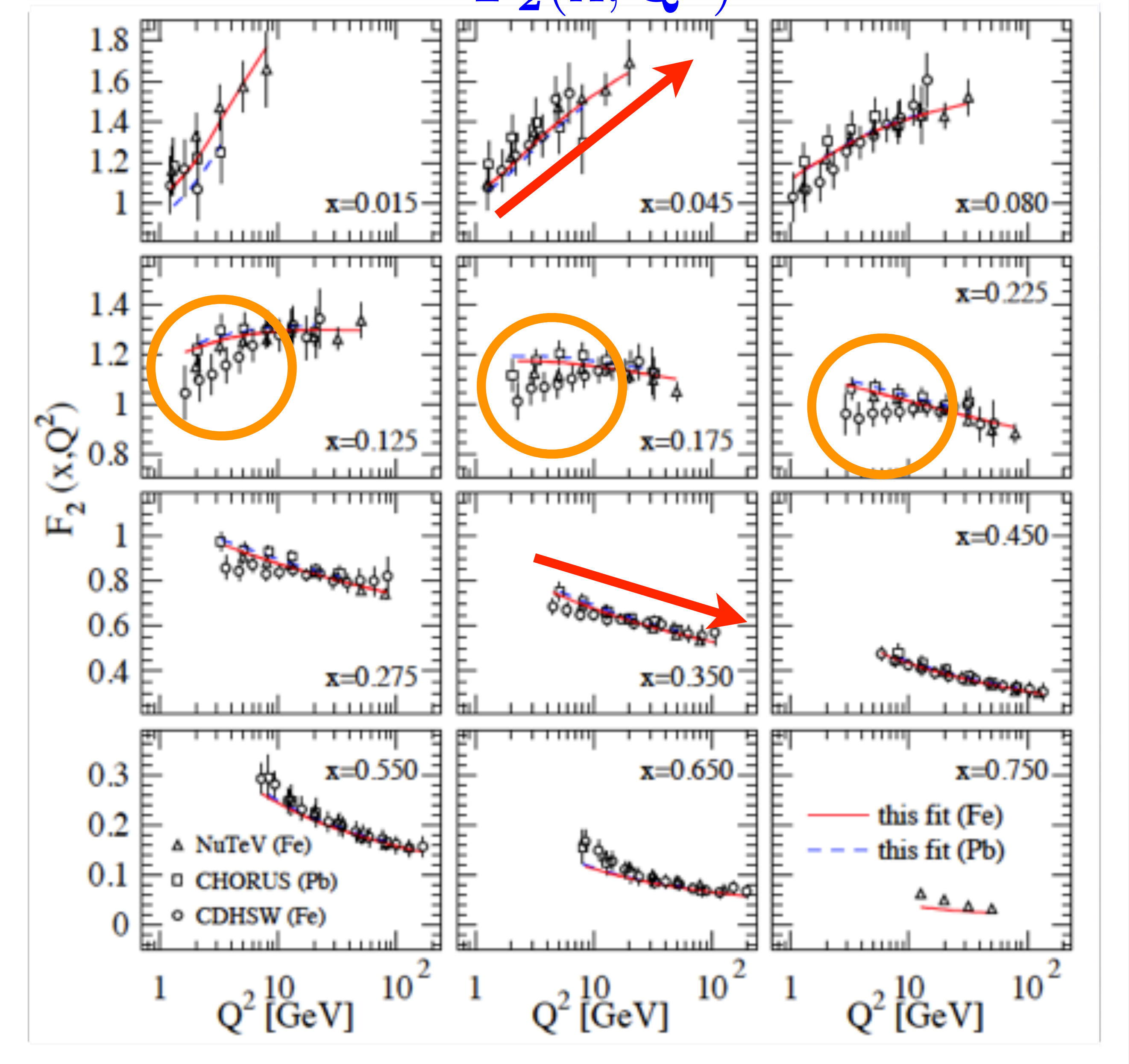

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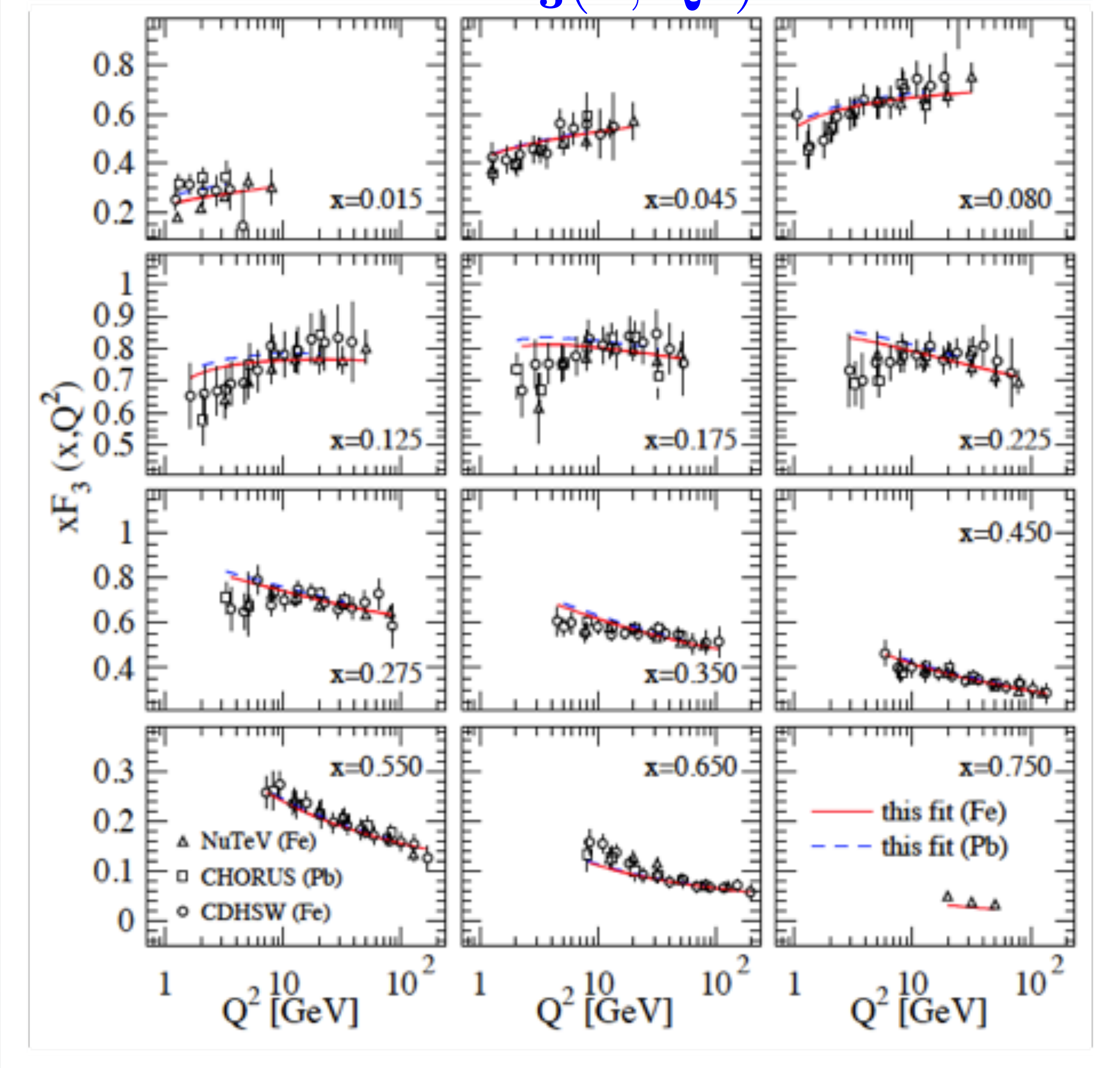

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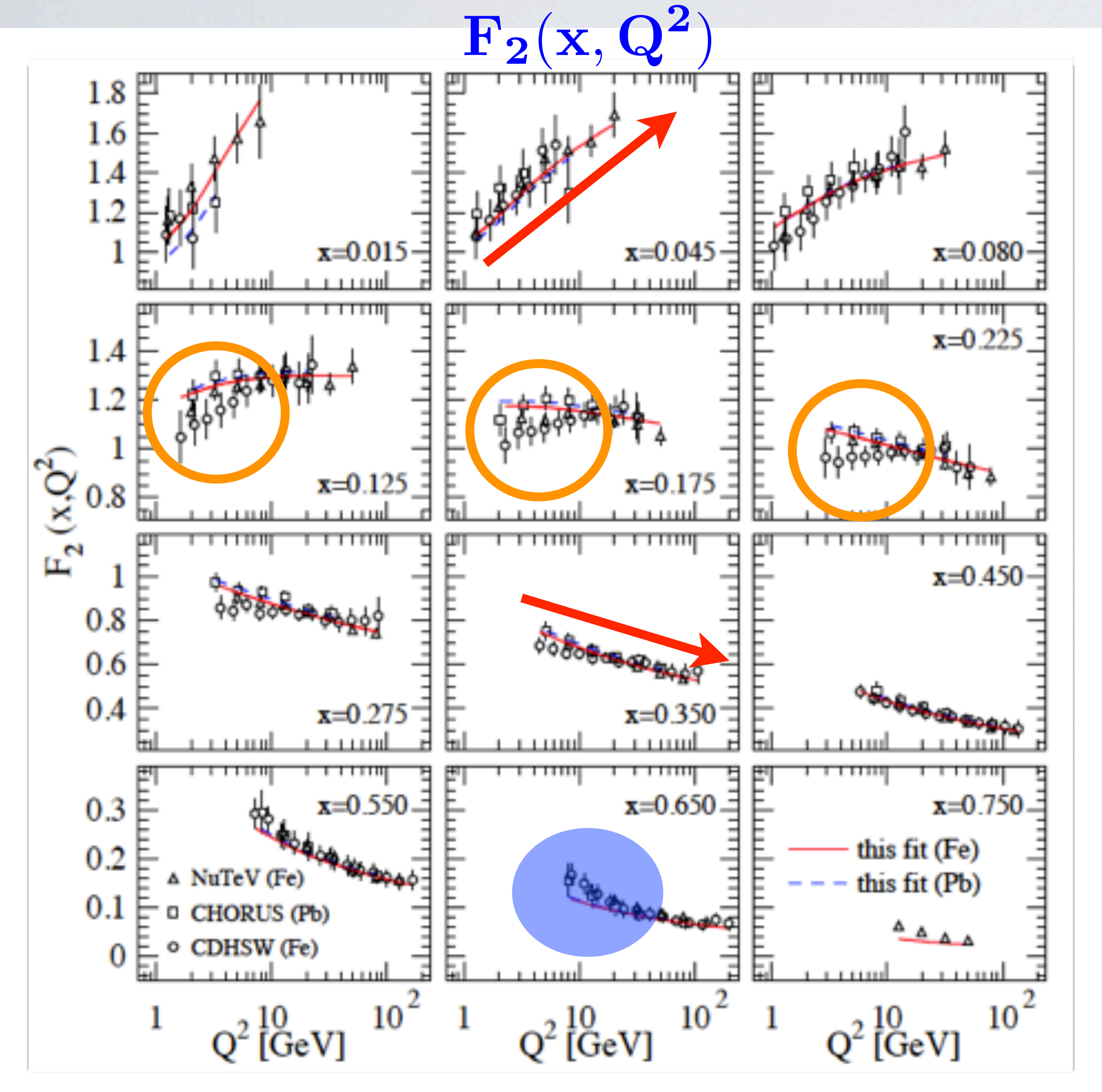

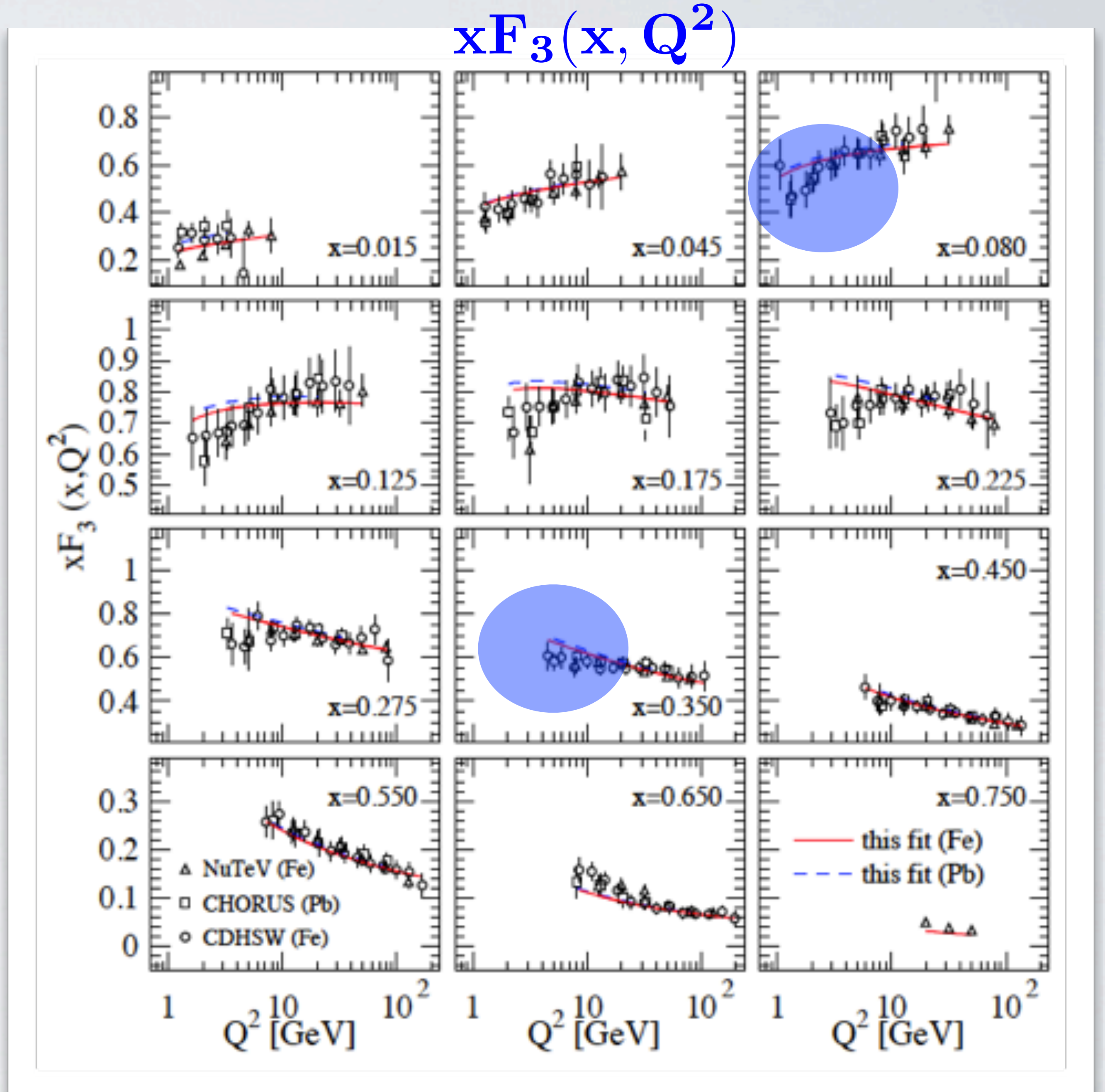

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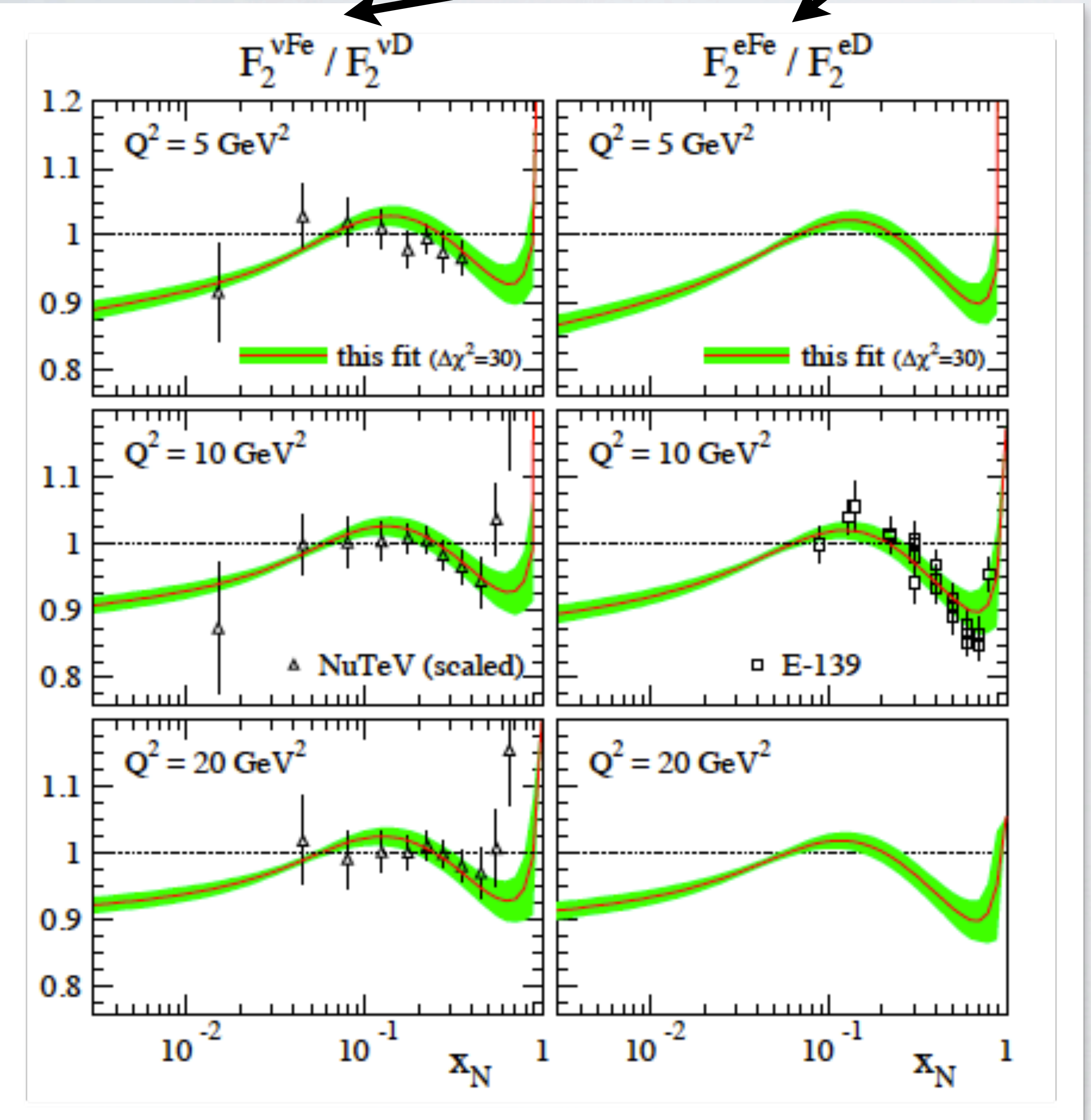
some mild tensions

often with CDHSW data

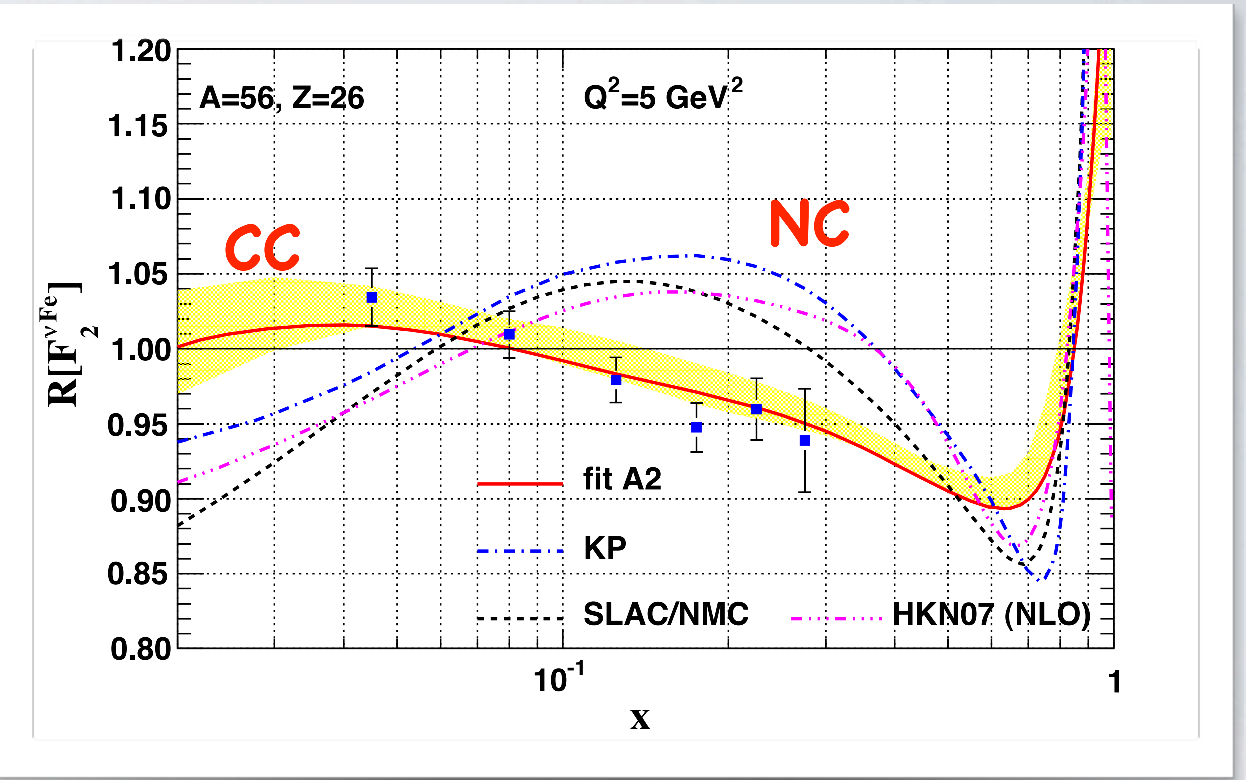
CC neutrino DIS data (cont'd)

no indication for factorization breaking

find same pattern of nuclear effects for CC and NC DIS



at variance with nCTEQ result



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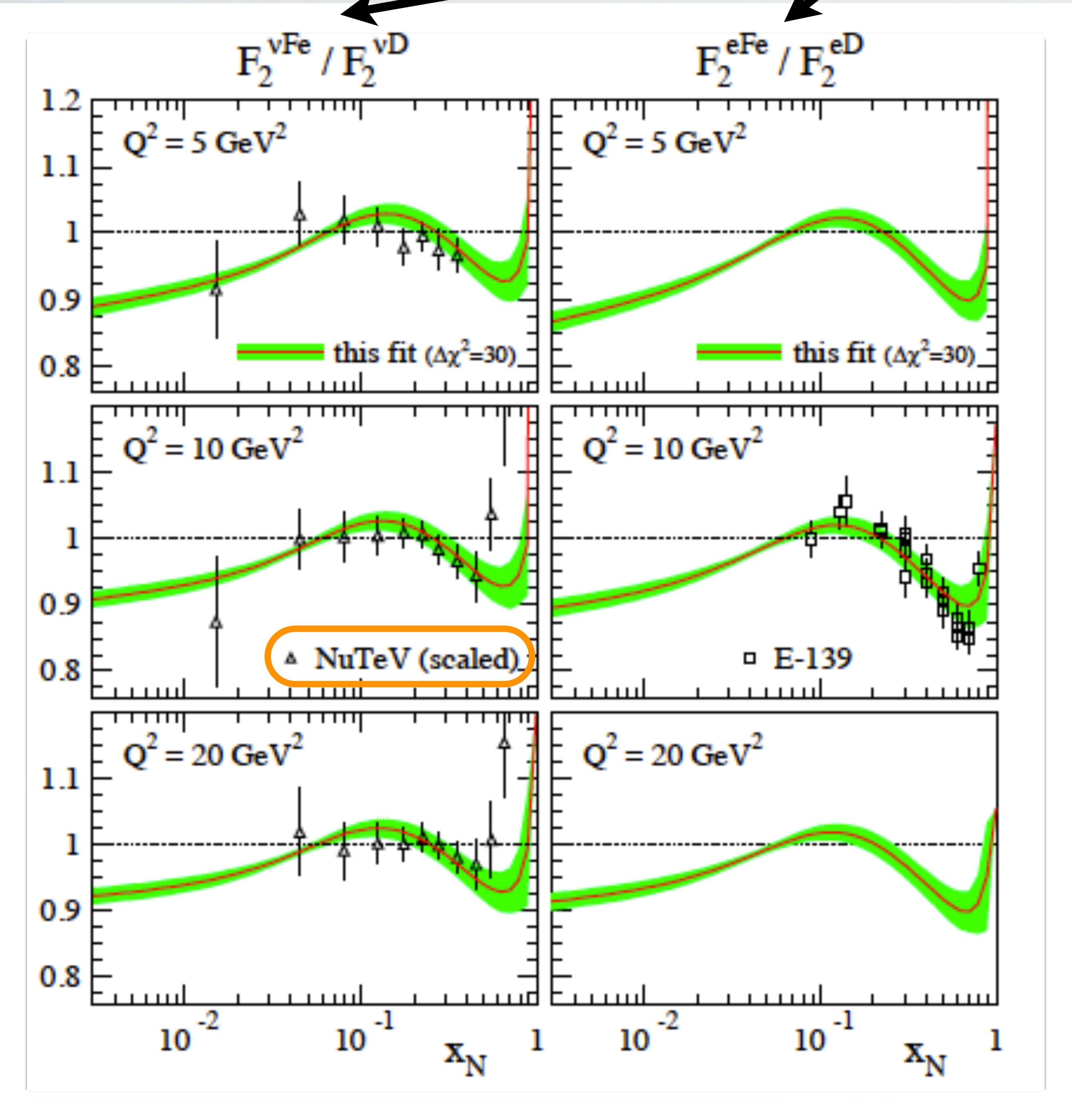

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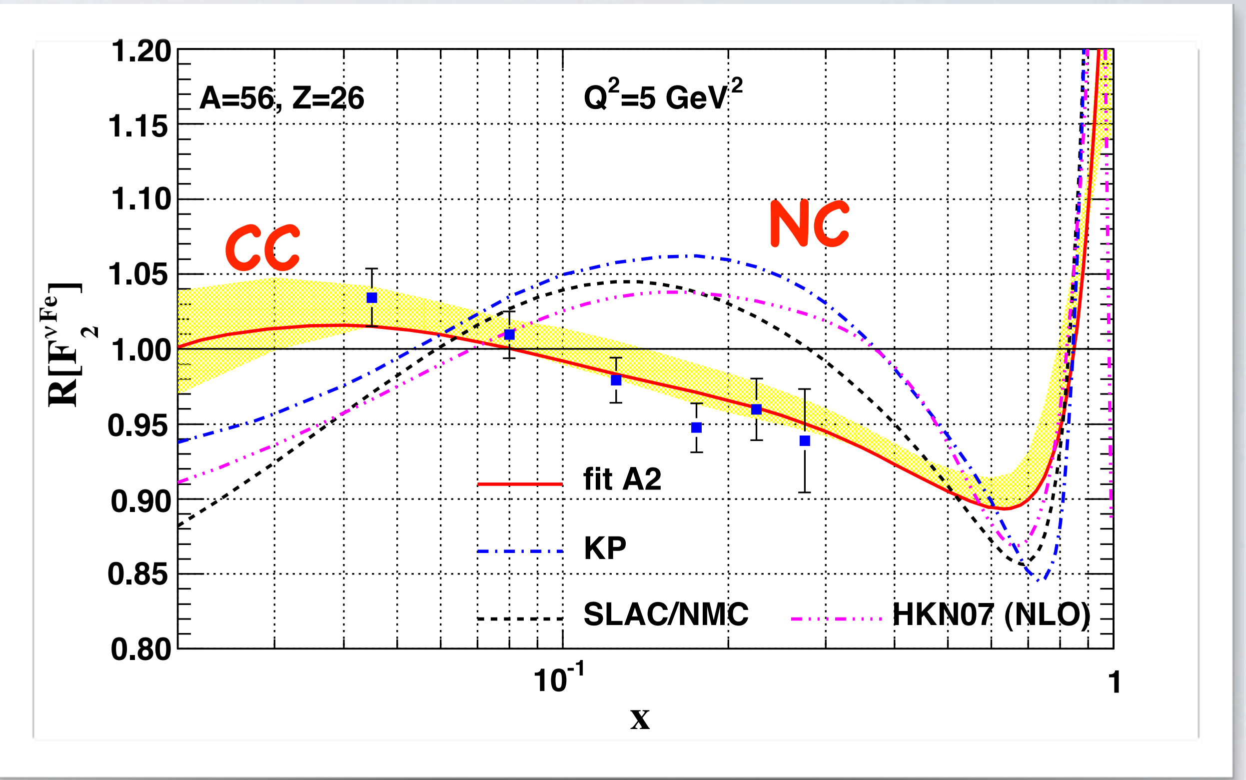

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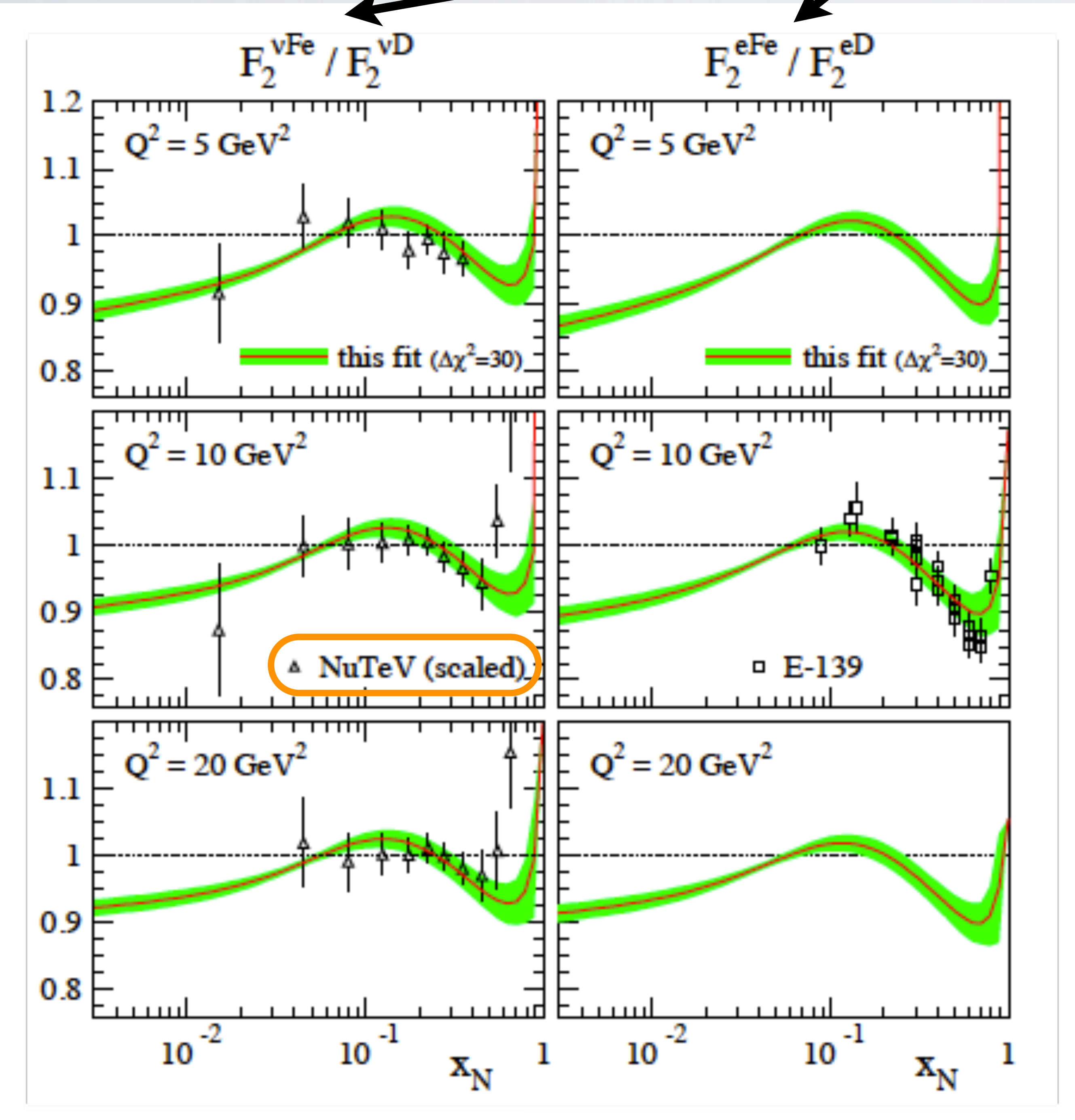

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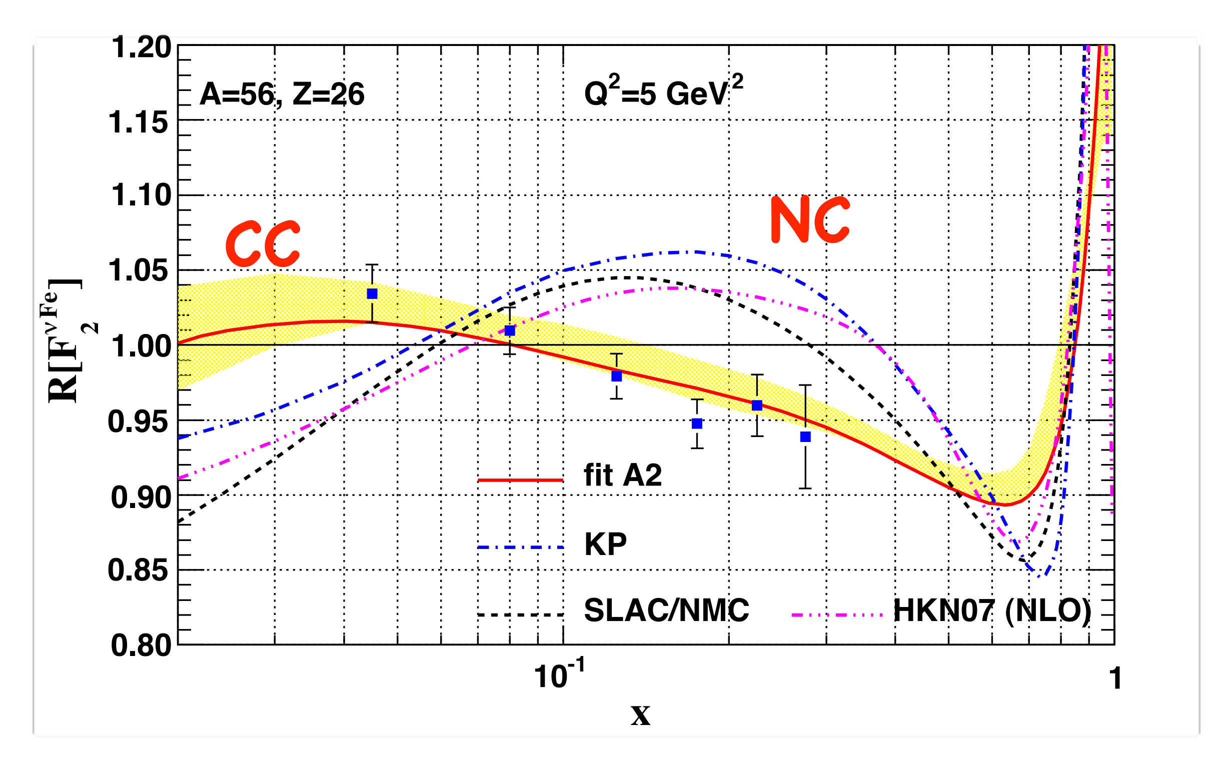

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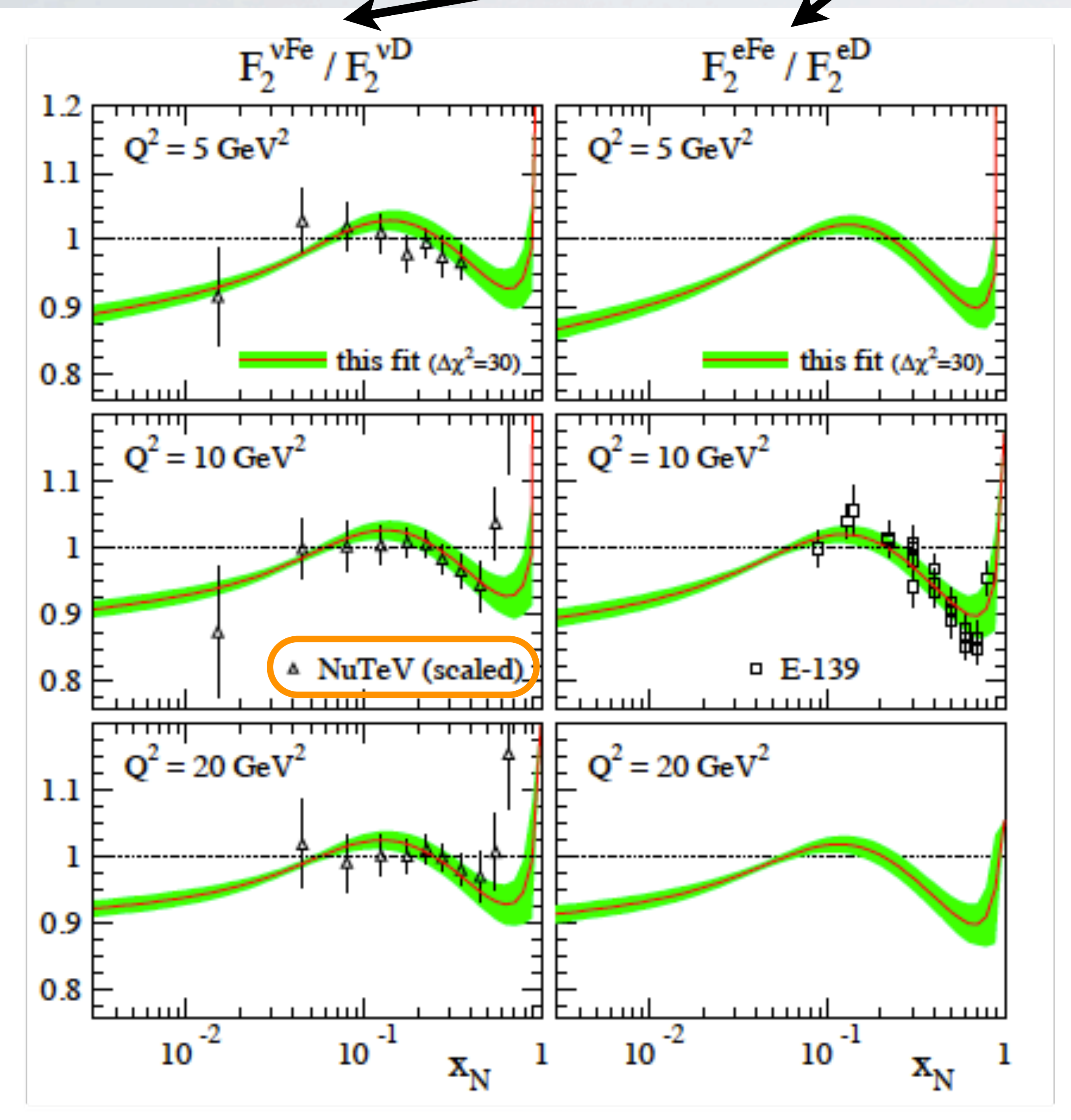
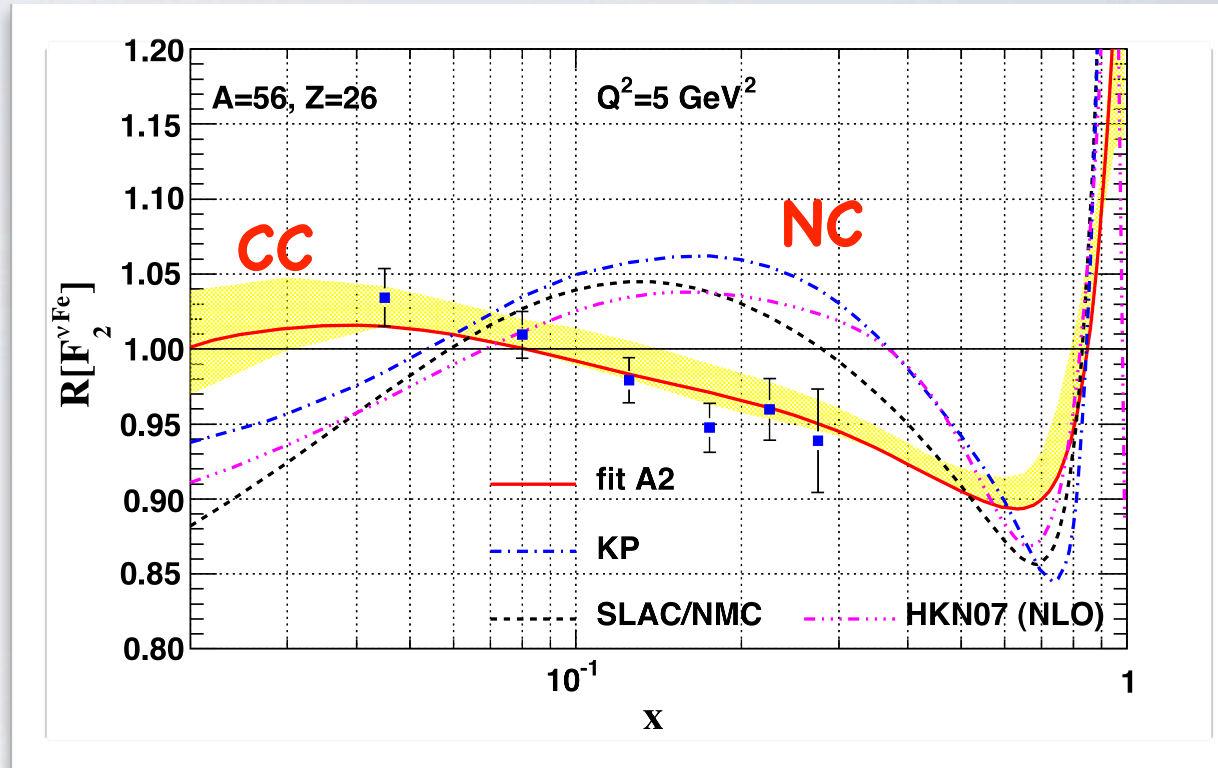
no indication for factorization breaking

find same pattern of nuclear effects for CC and NC DIS



at variance with nCTEQ result



- "theoretical data": $\mathbf{F_2^{\nu D}}$ not measured
- nCTEQ fits to cross sections not str. fcts.
- also EPS finds compatible nuclear effects
  (no re-fit including CC DIS yet)

pion production in dA

most difficult probe to analyze (yet, perhaps one of the most interesting ones)

$$\mathbf{d\sigma^{A}_{dA\to\pi X} = \sum_{ijk} f^{d}_{i} \otimes \boxed{f^{A}_{j}} \otimes d\hat{\sigma}_{ij\to kX} \otimes D^{A,\pi}_{k}}$$

wanted

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free proton PDF
"known"

wanted

known to NLO
[plus certain all-order resummations]
many contributing subprocesses

fragmentation functions
fairly well known for pions
but what about possible nuclear modifications?
can have an impact even if small

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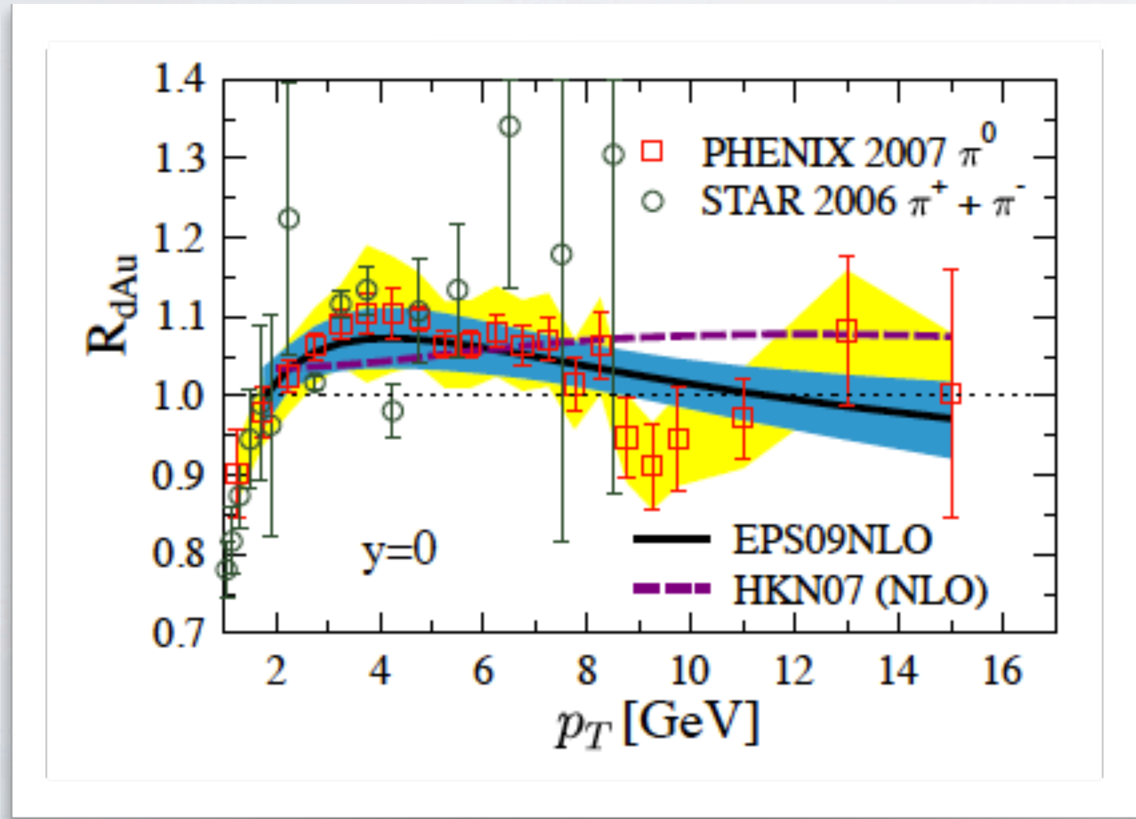

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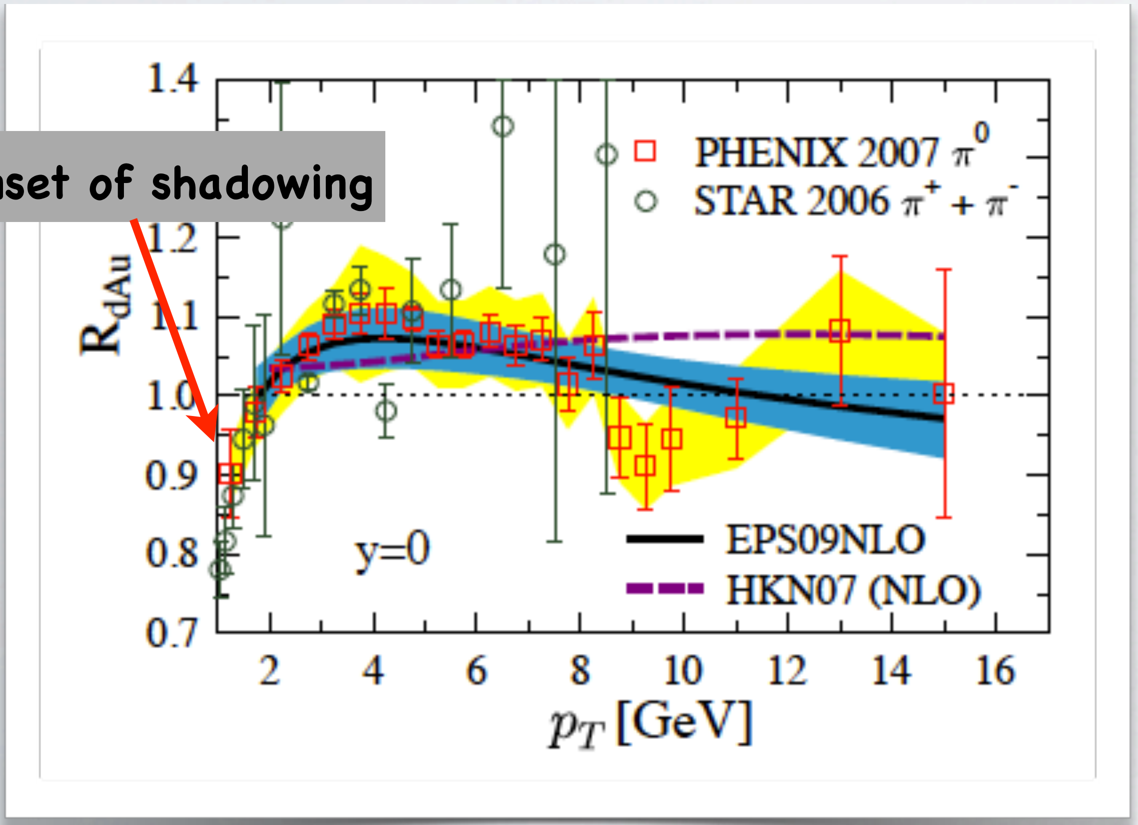

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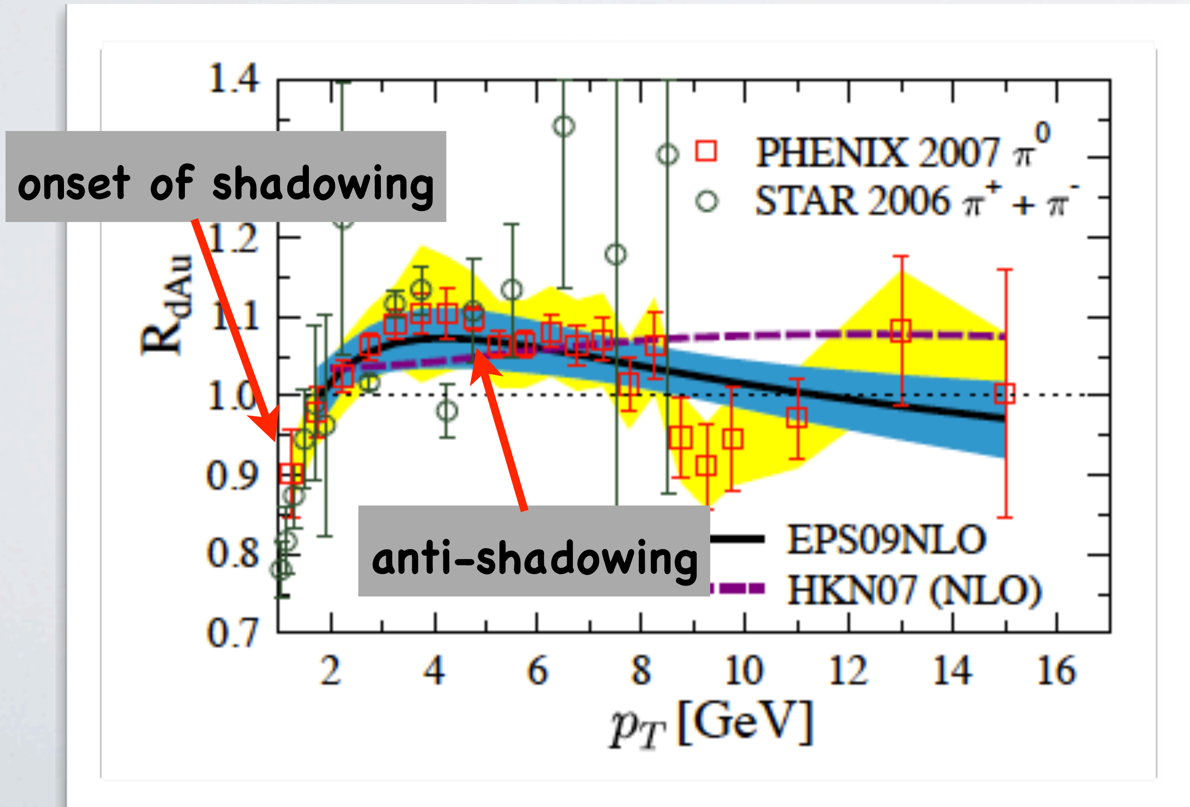

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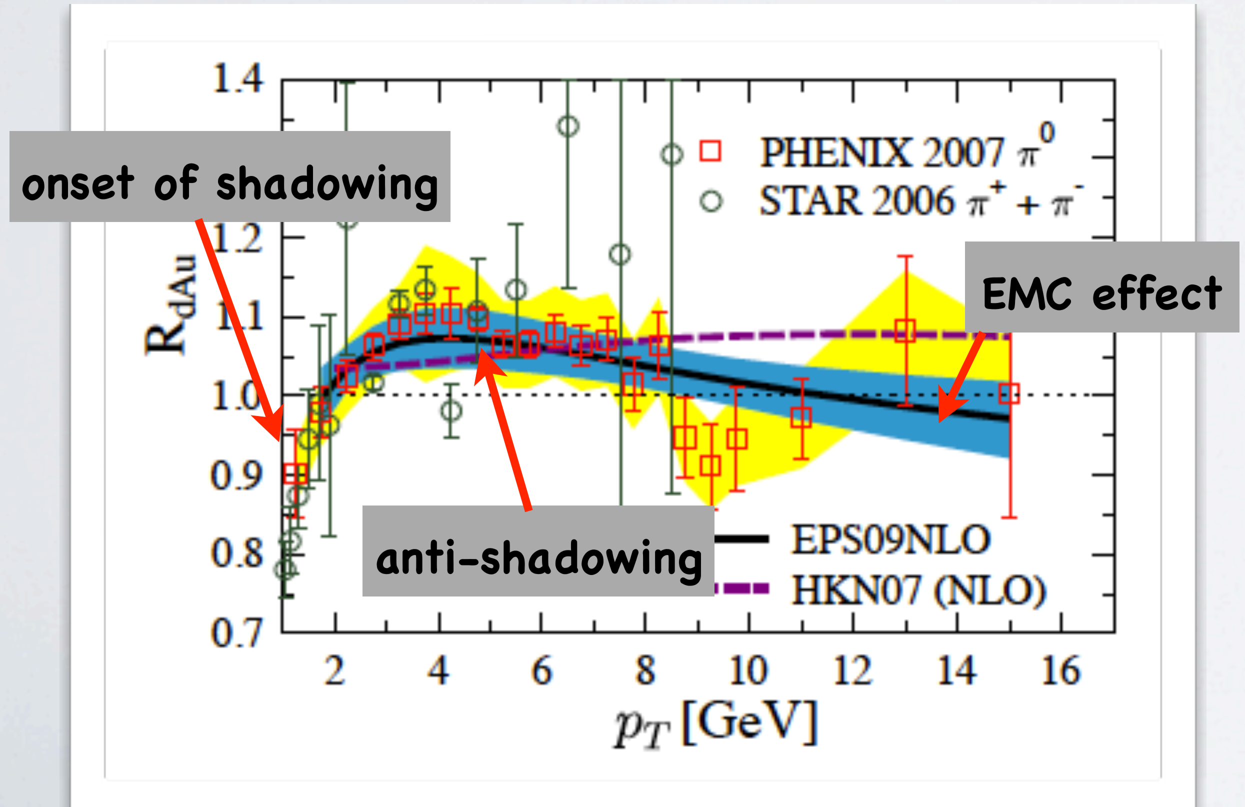

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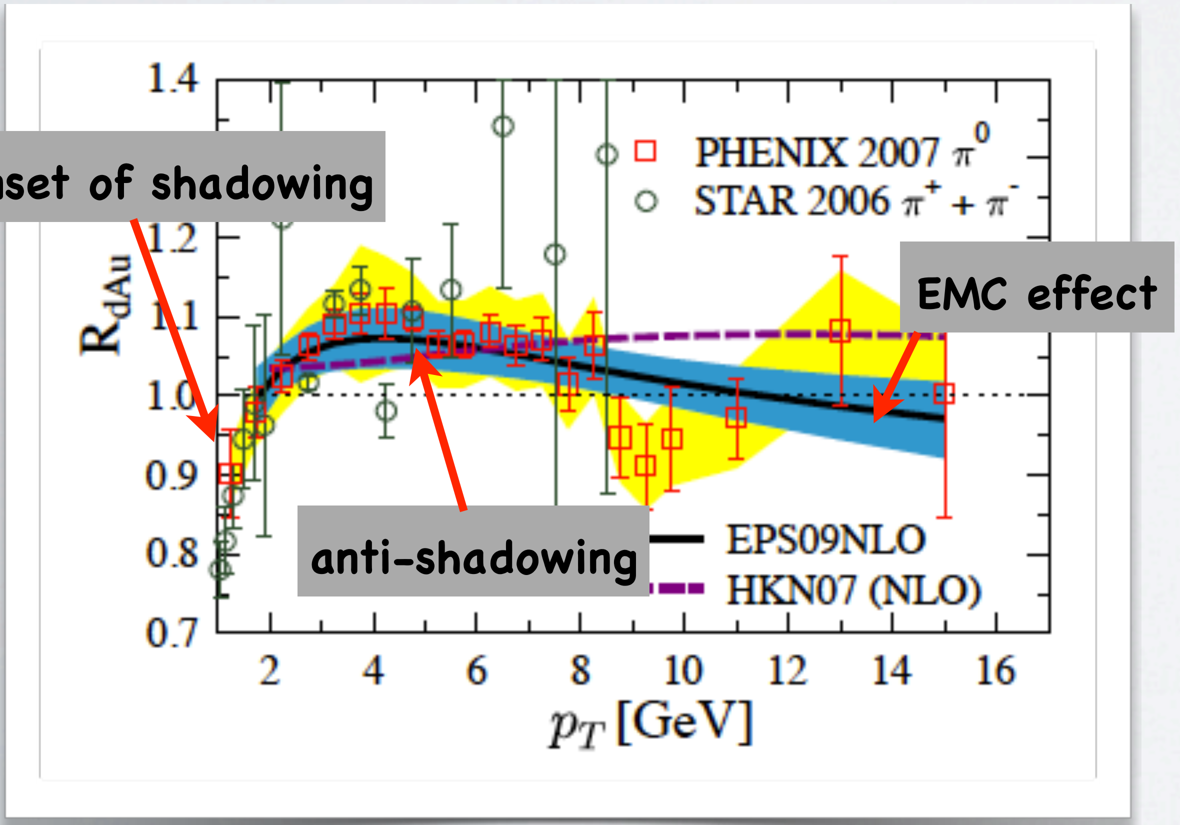

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potential caveat: need to assign large weight to dAu data in fit

pion production in dA - cont'd

what is different in DSSZ analysis

- ✓ more data, including also charged pions from STAR
- ✓ no artificially large weight w.r.t. other data sets
- ✓ try to estimate impact of modifications in hadronization

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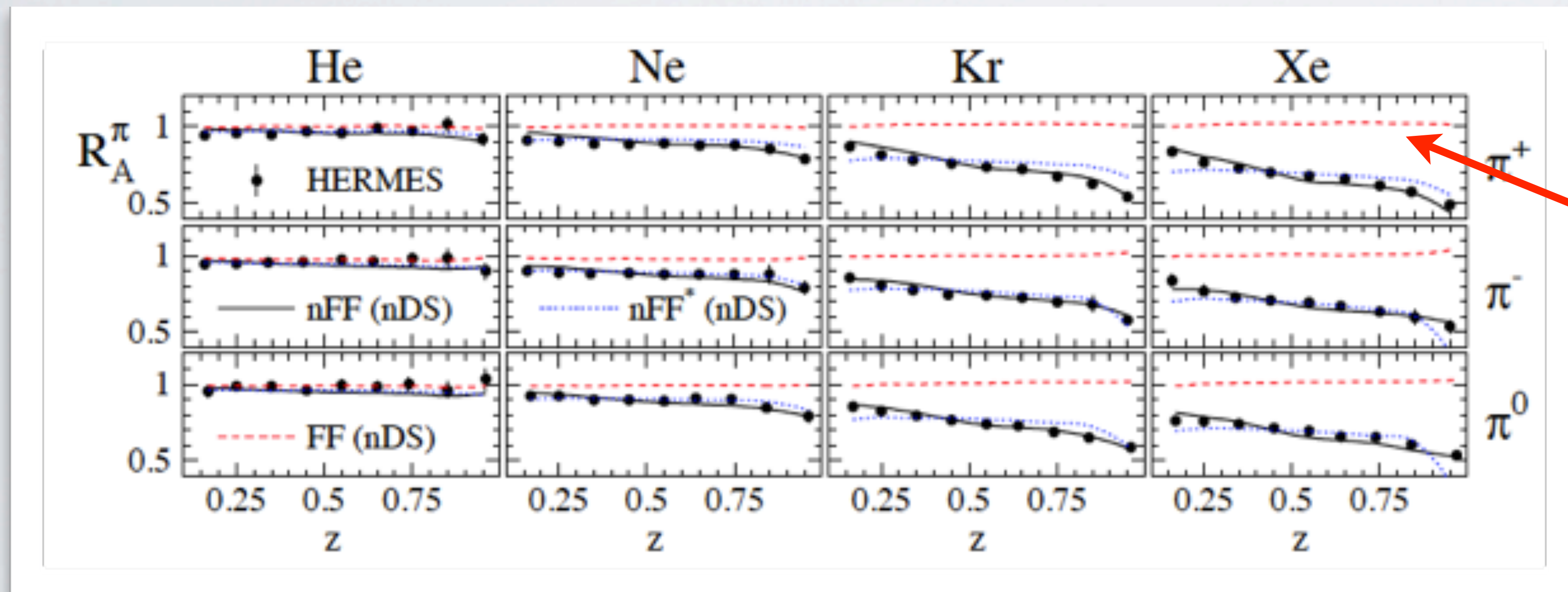
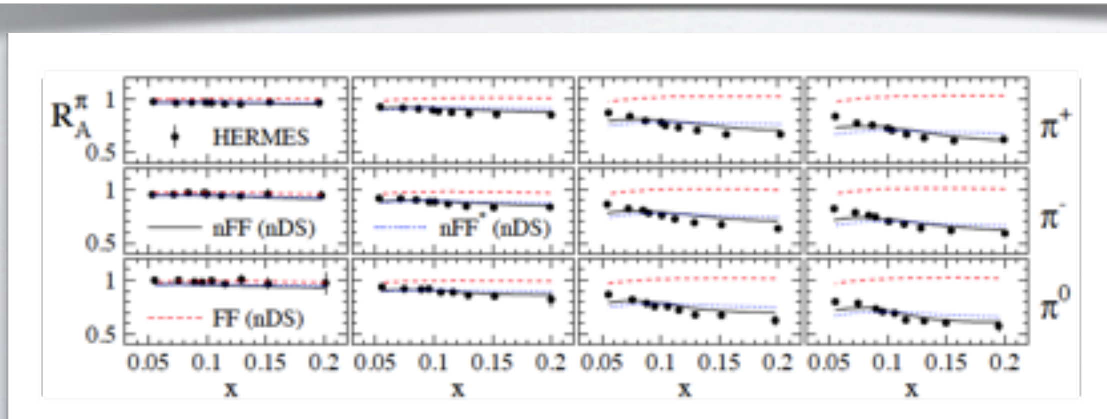
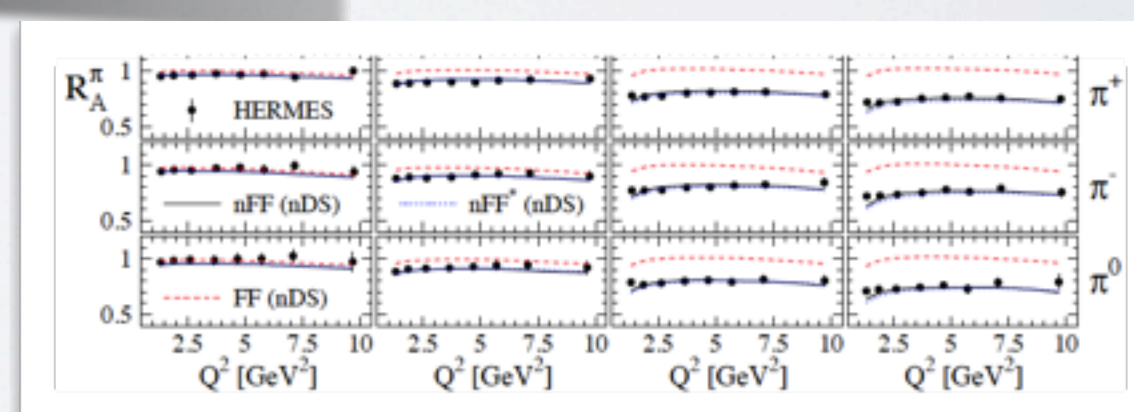
fragmentation in a medium - what is known ?



- effects known to be large in eA
- cannot be described as an initial-state effect (= nPDFs)
- hadron attenuation increases with A and z (rather flat in x and Q^2)

HERMES





medium modified fragmentation

how to model fragmentation in a medium ?

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bold attempt: extend FFs to medium modified FFs ("in the background of a nucleus A") Sassot, MS, Zurita 0912.1311

choose convolution ansatz to modify vacuum FFs

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$$\mathbf{D^H_{i/A}(z, Q_0) = \int_z^1 \frac{dy}{y} W_i(y, A)\, D^H_i(\frac{z}{y}, Q_0)}$$

from fit to HERMES and RHIC dAu pion data

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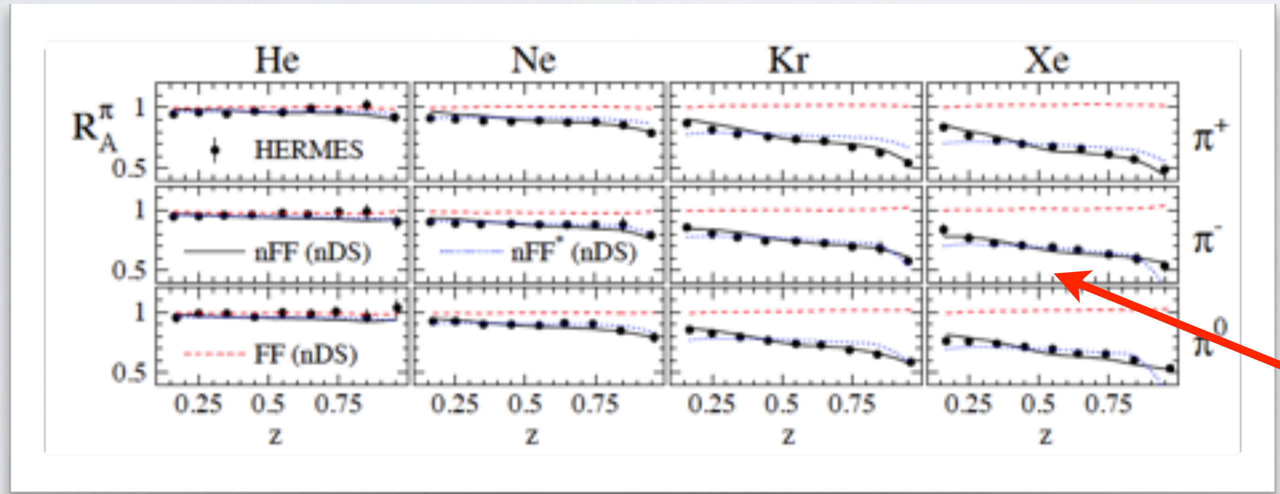

works well

Experiment	A	H	Data type	Data points	χ^2
HERMES [6]	He,Ne,Kr,Xe	π^+	z	36	39.3
		π^-	z	36	23.0
		π^0	z	36	27.4
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		π^-	x	36	55.4
		π^0	x	36	49.7
		π^+	Q^2	32	21.0
		π^-	Q^2	32	27.1
		π^0	Q^2	32	34.7
PHENIX [14]	Au	π^0	p_T	22	13.7
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Total				381	396.0

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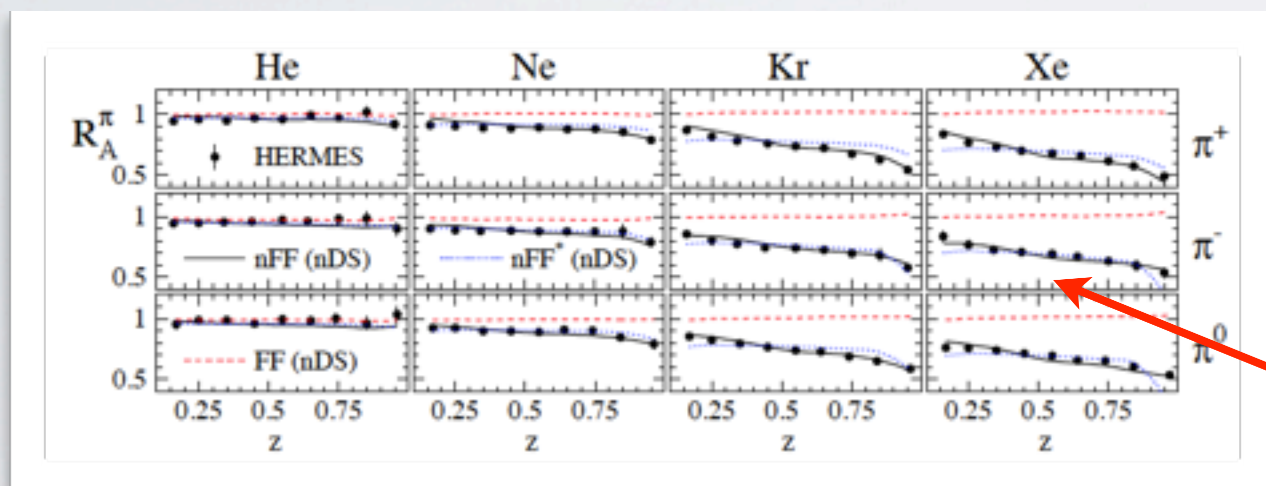

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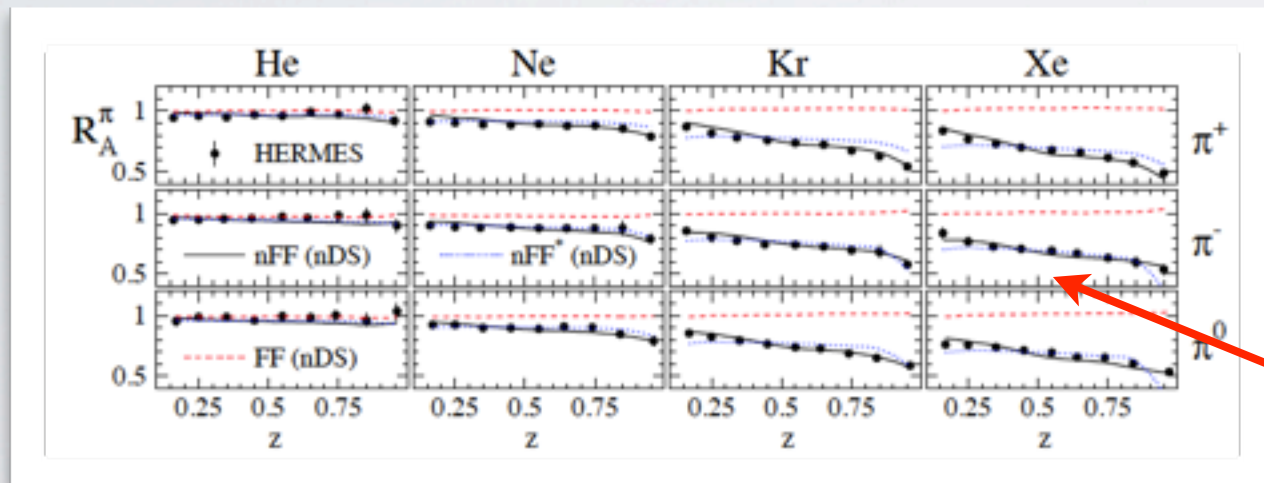

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use both DSS vacuum and effective nuclear FFs in DSSZ nPDF analysis

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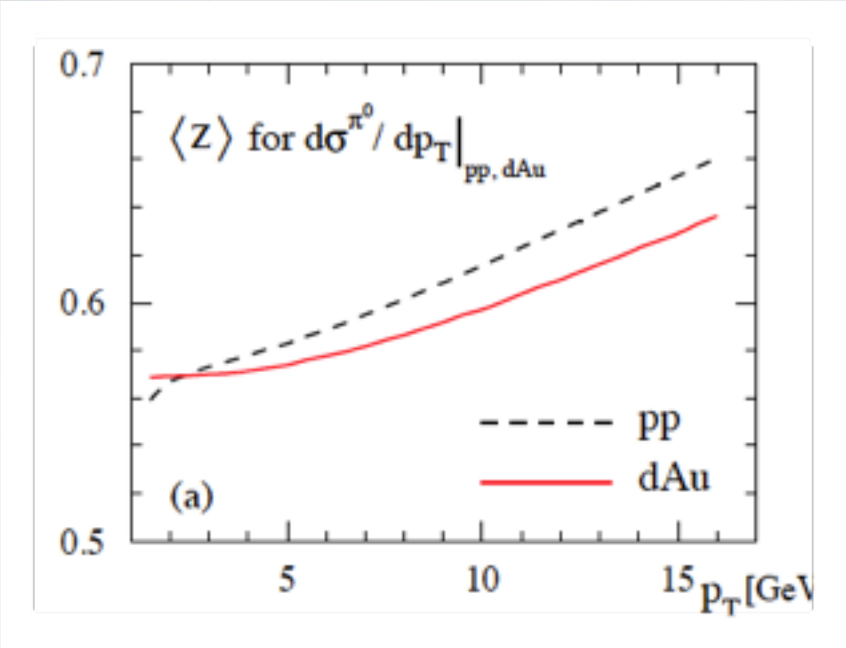
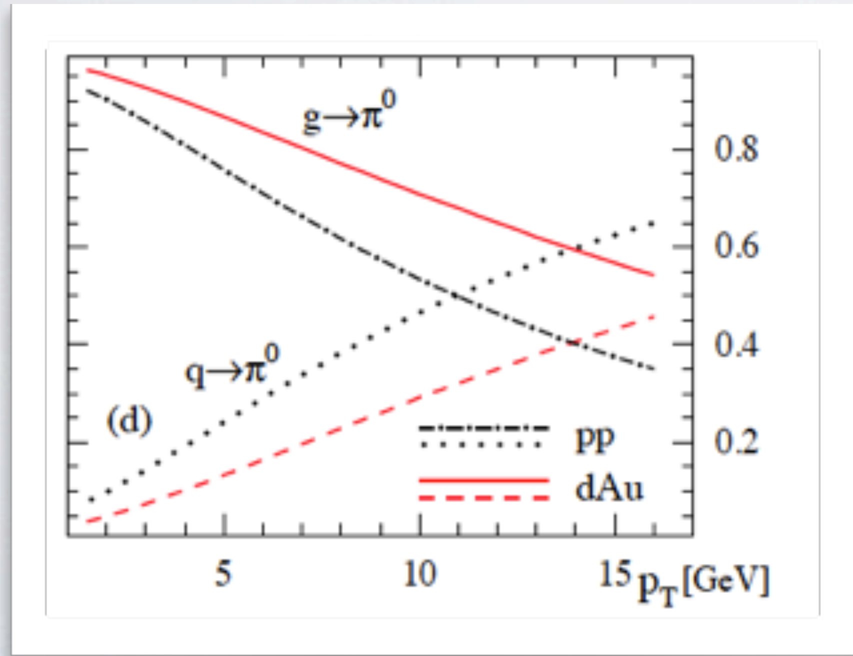
at RHIC (mid rapidity) we probe large z
and mostly pions from gluons





Sassot, MS, Zurita 0912.1311

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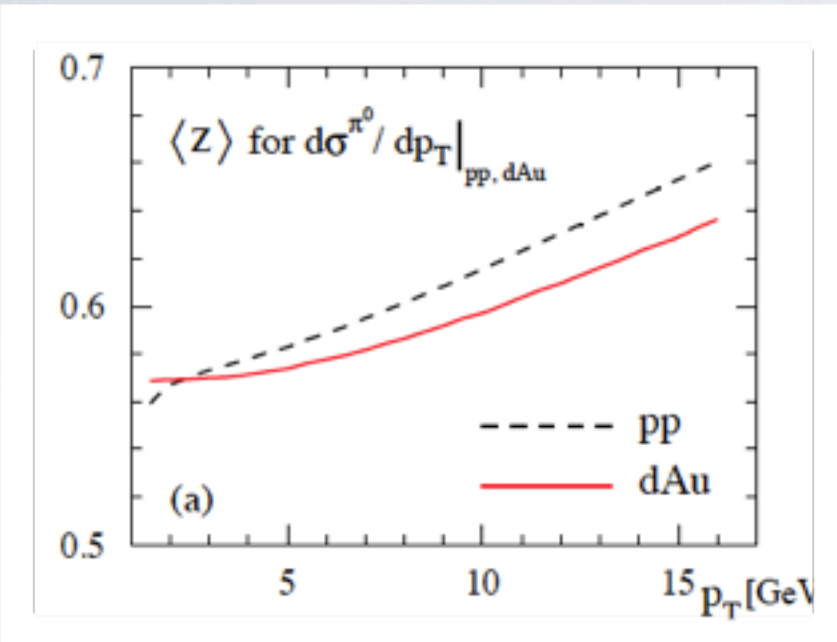
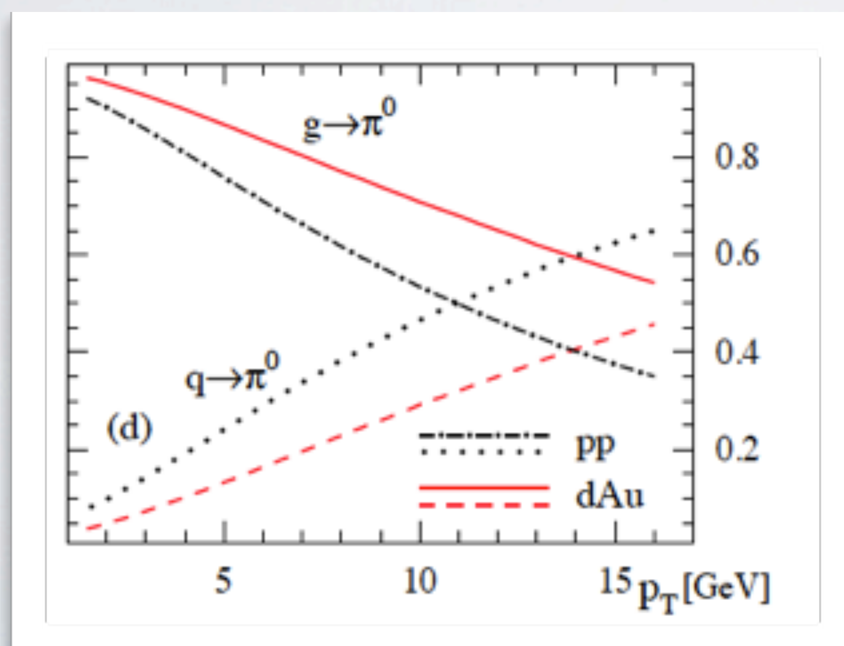
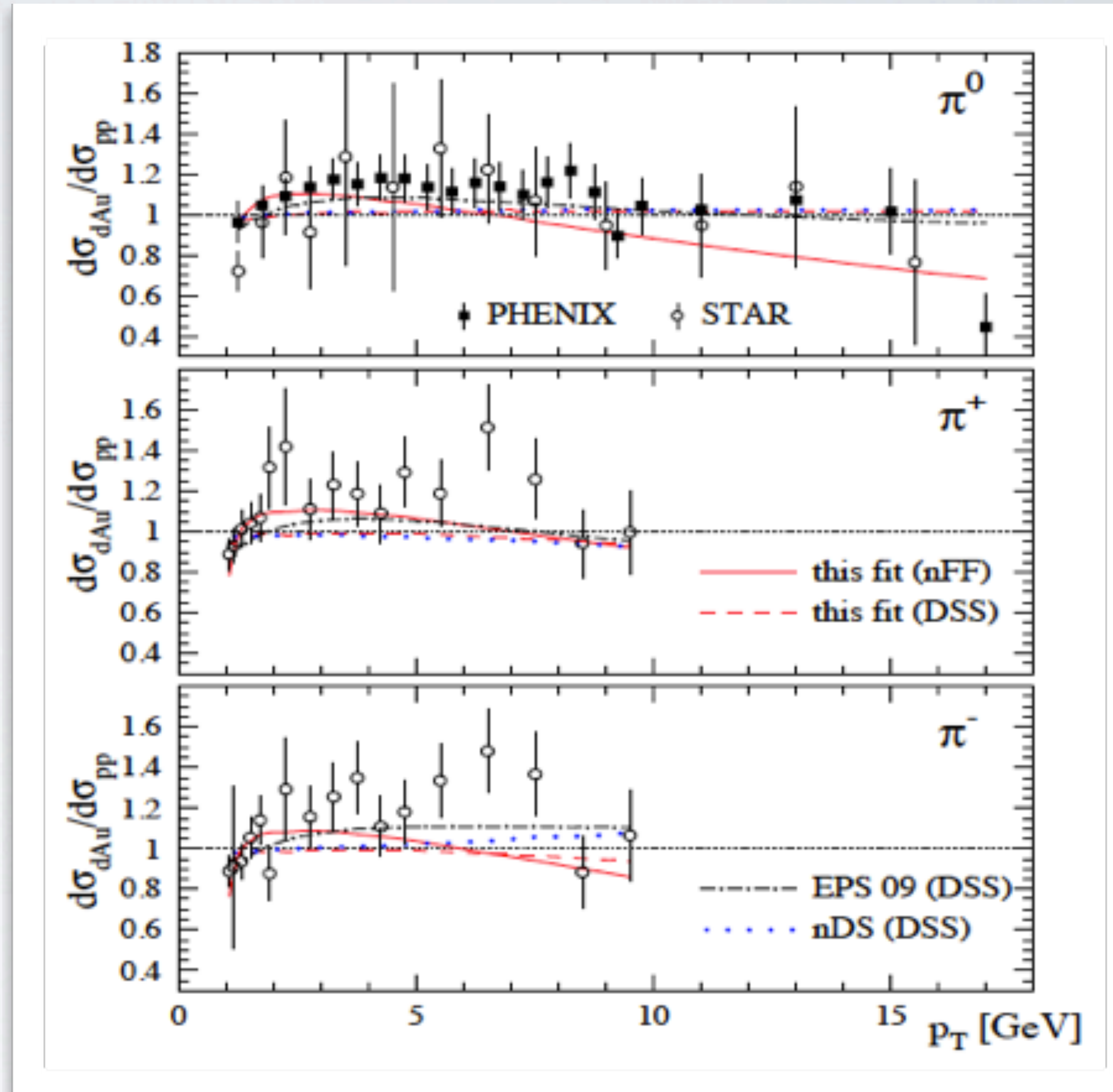




Sassot, MS, Zurita 0912.1311

result of our nPDF fit



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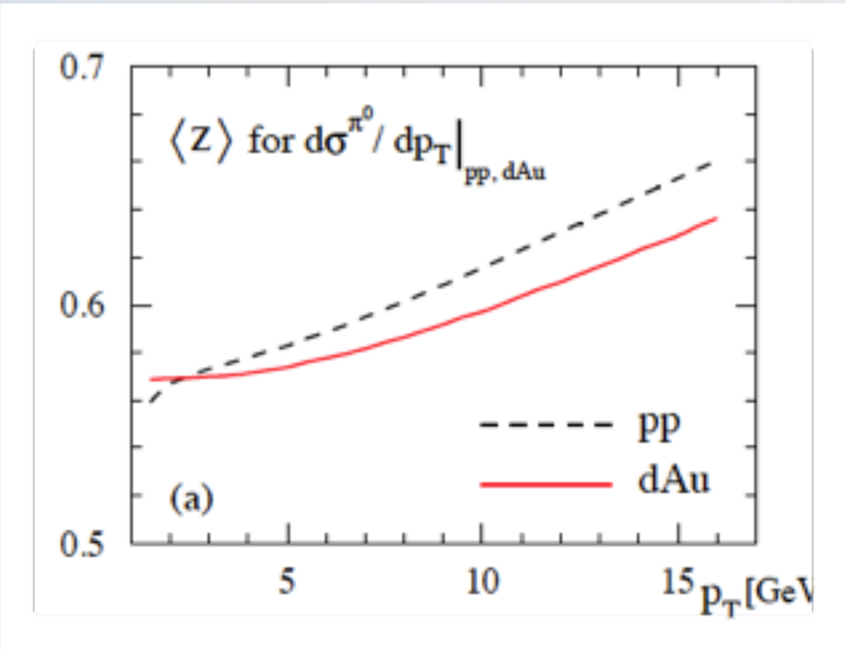

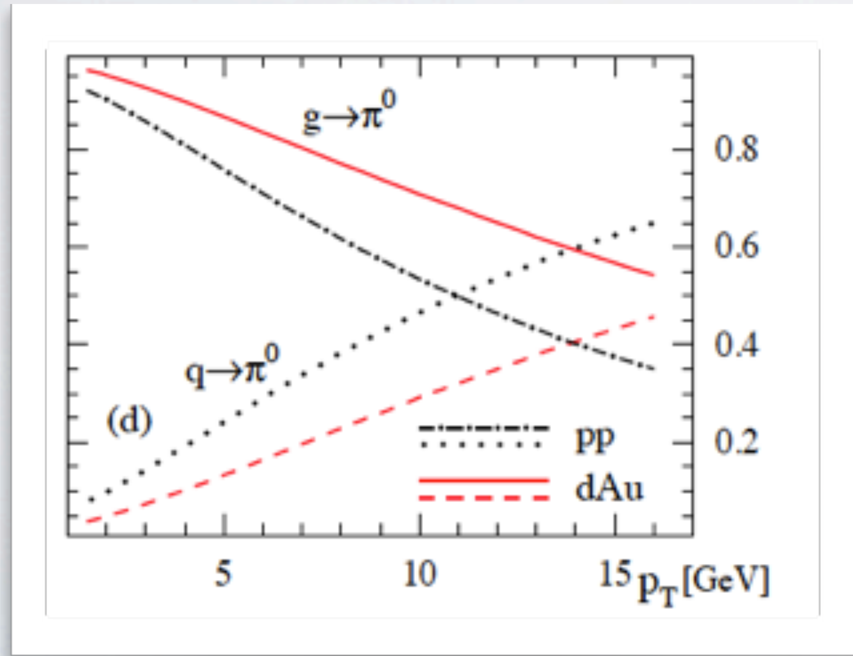

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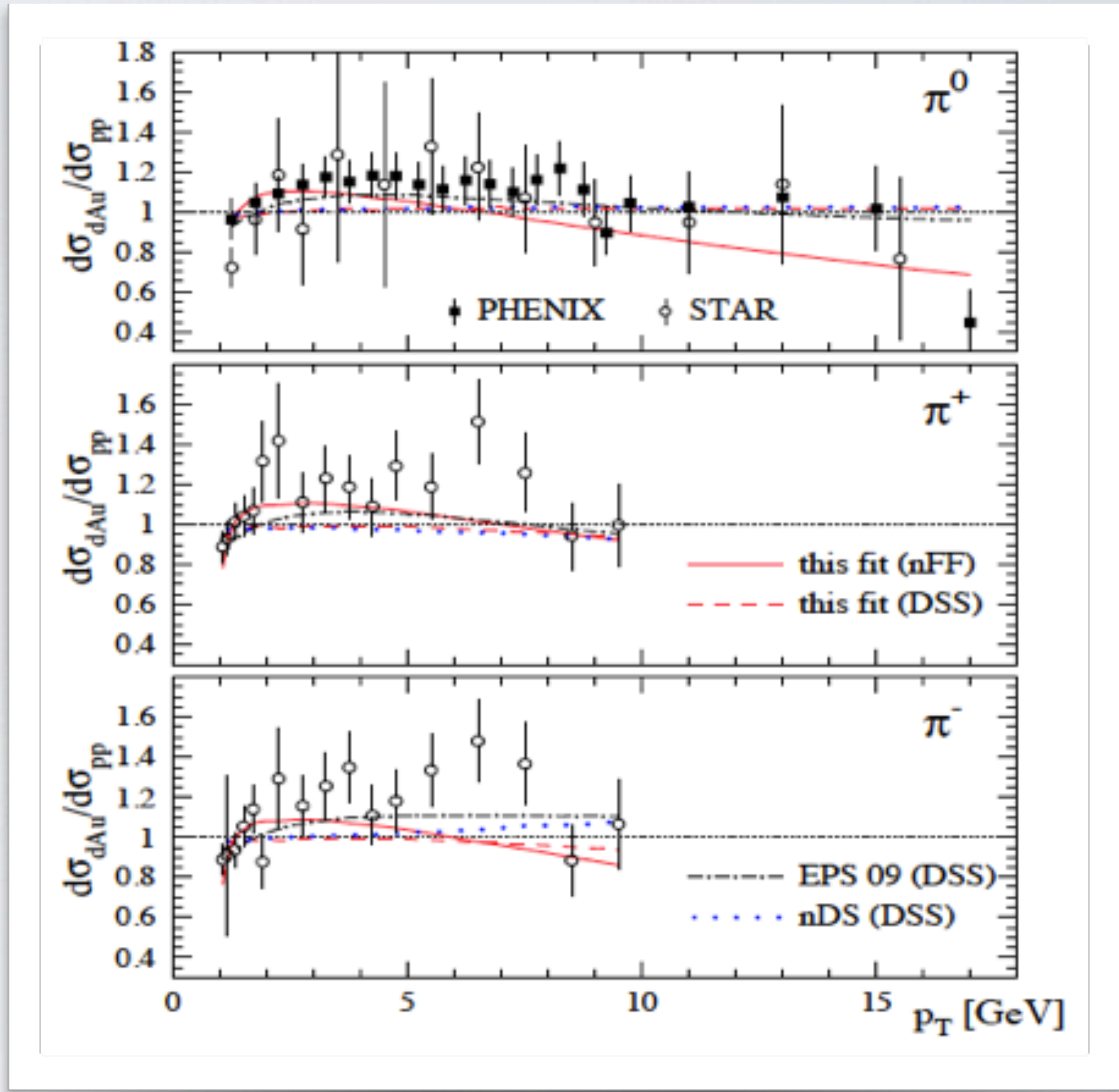

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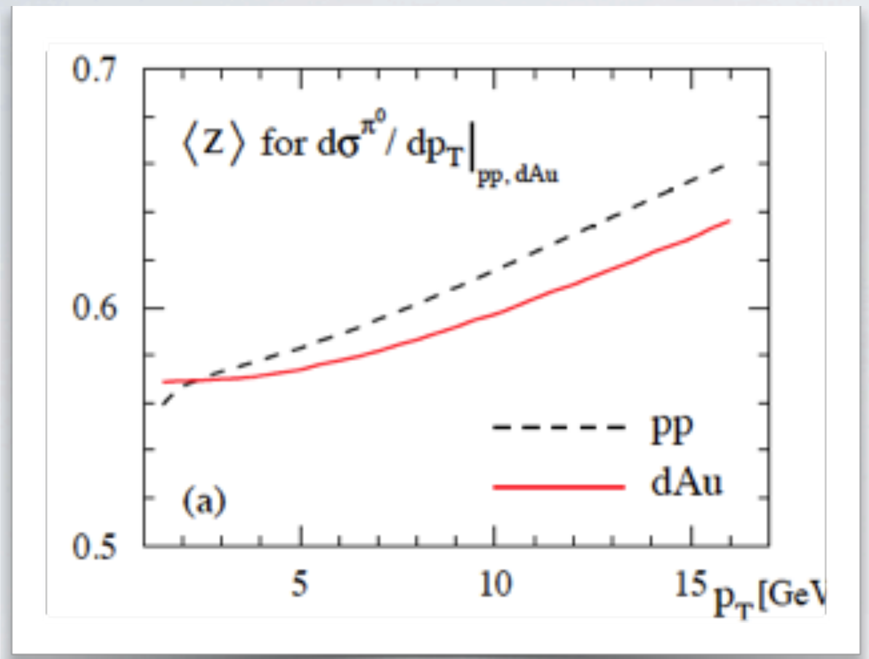

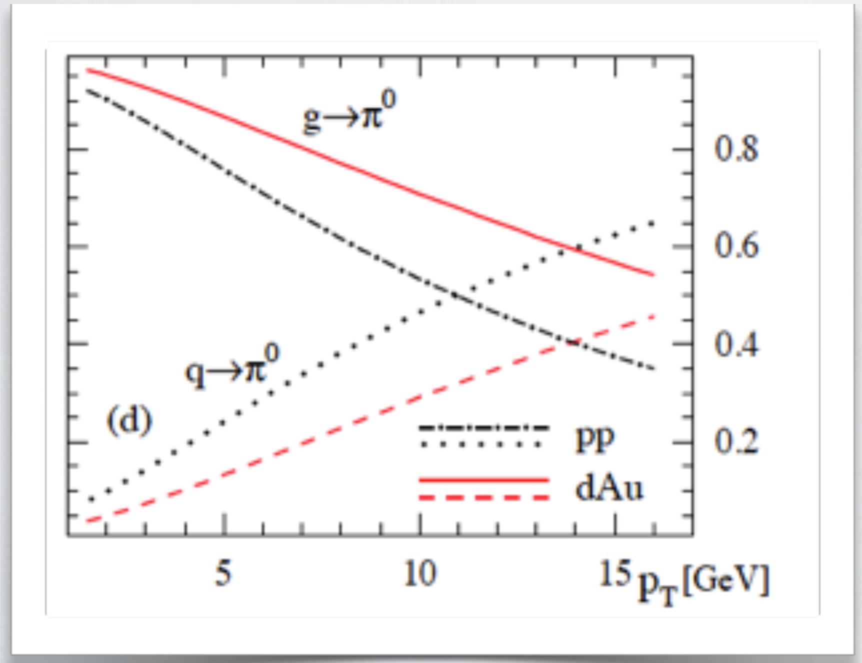

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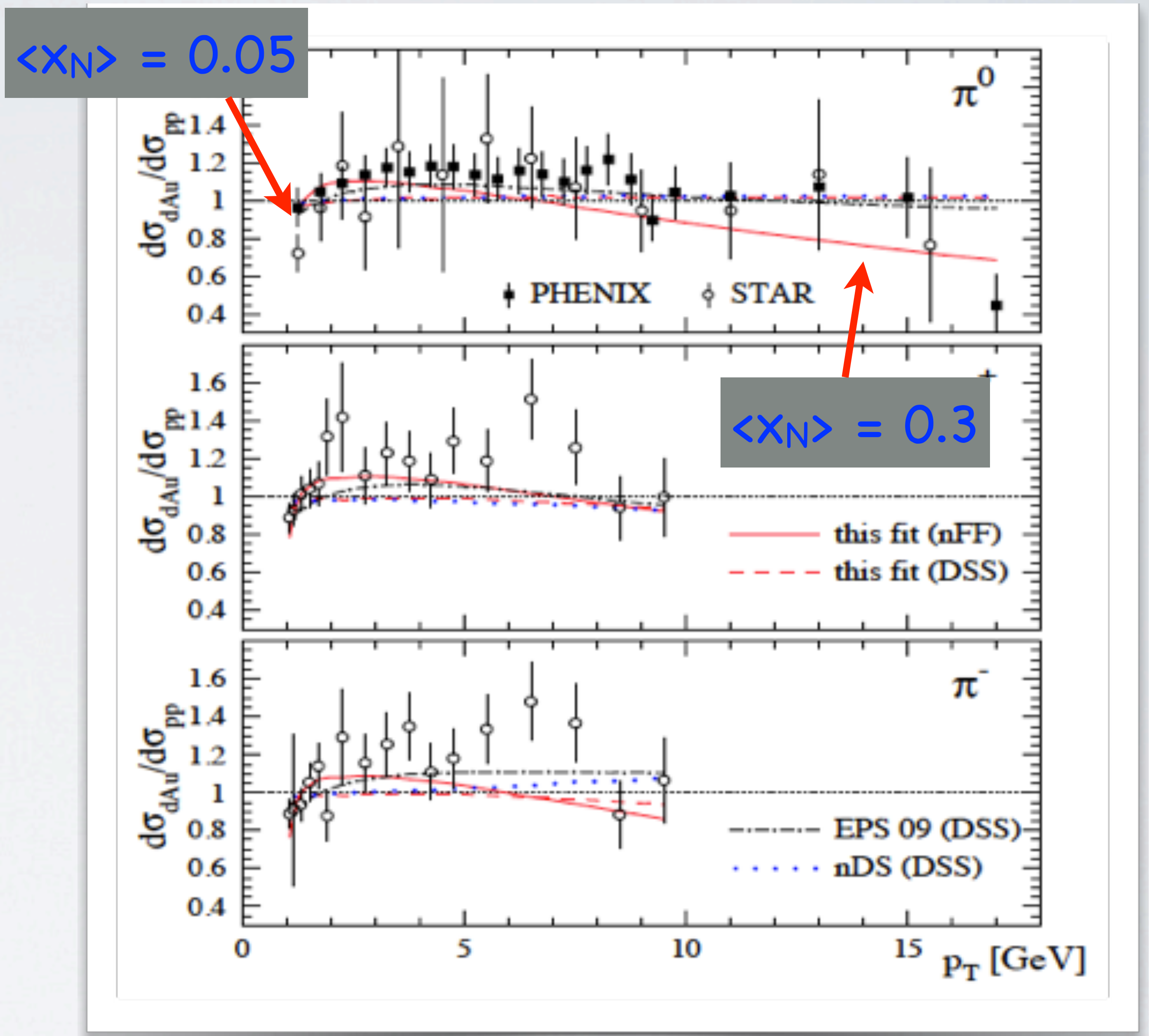

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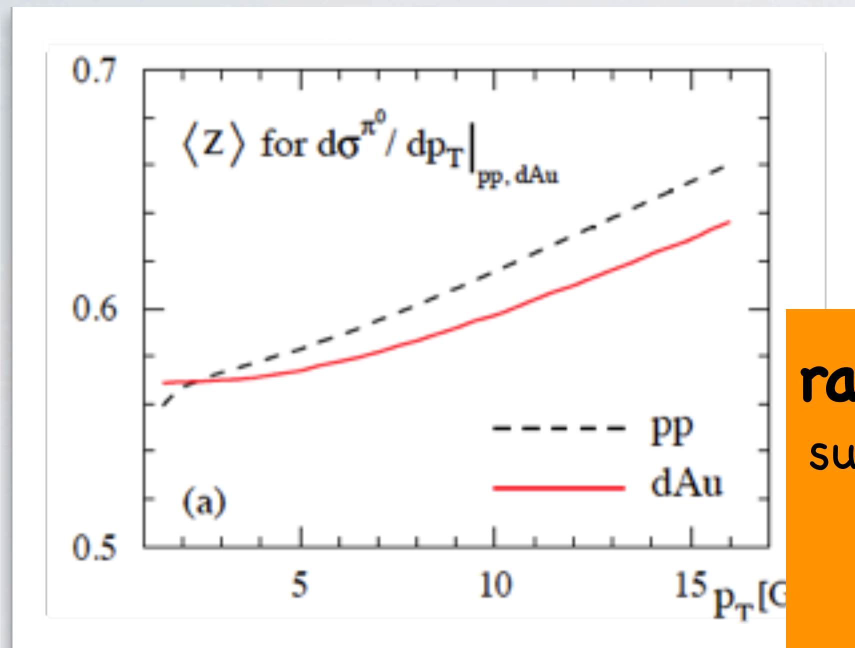

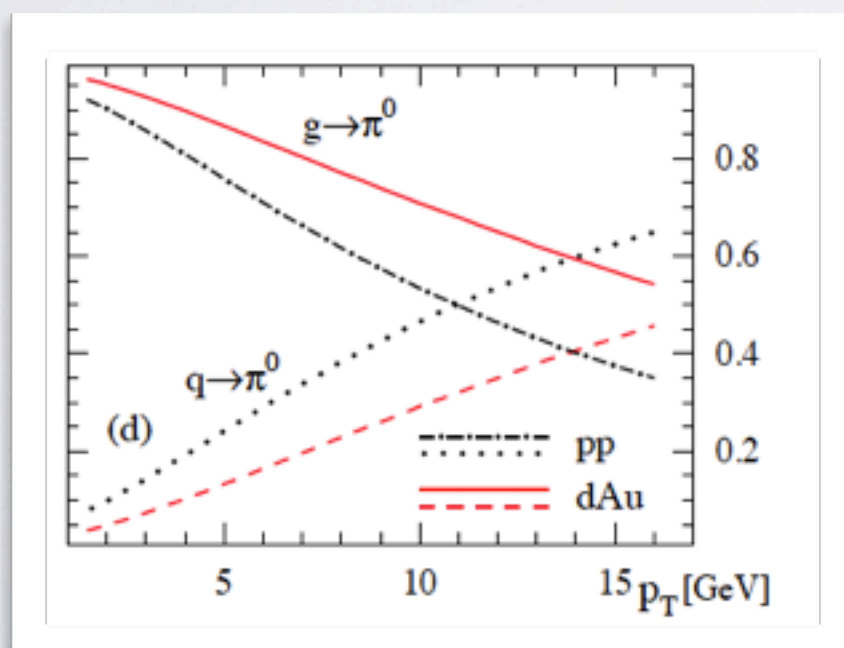

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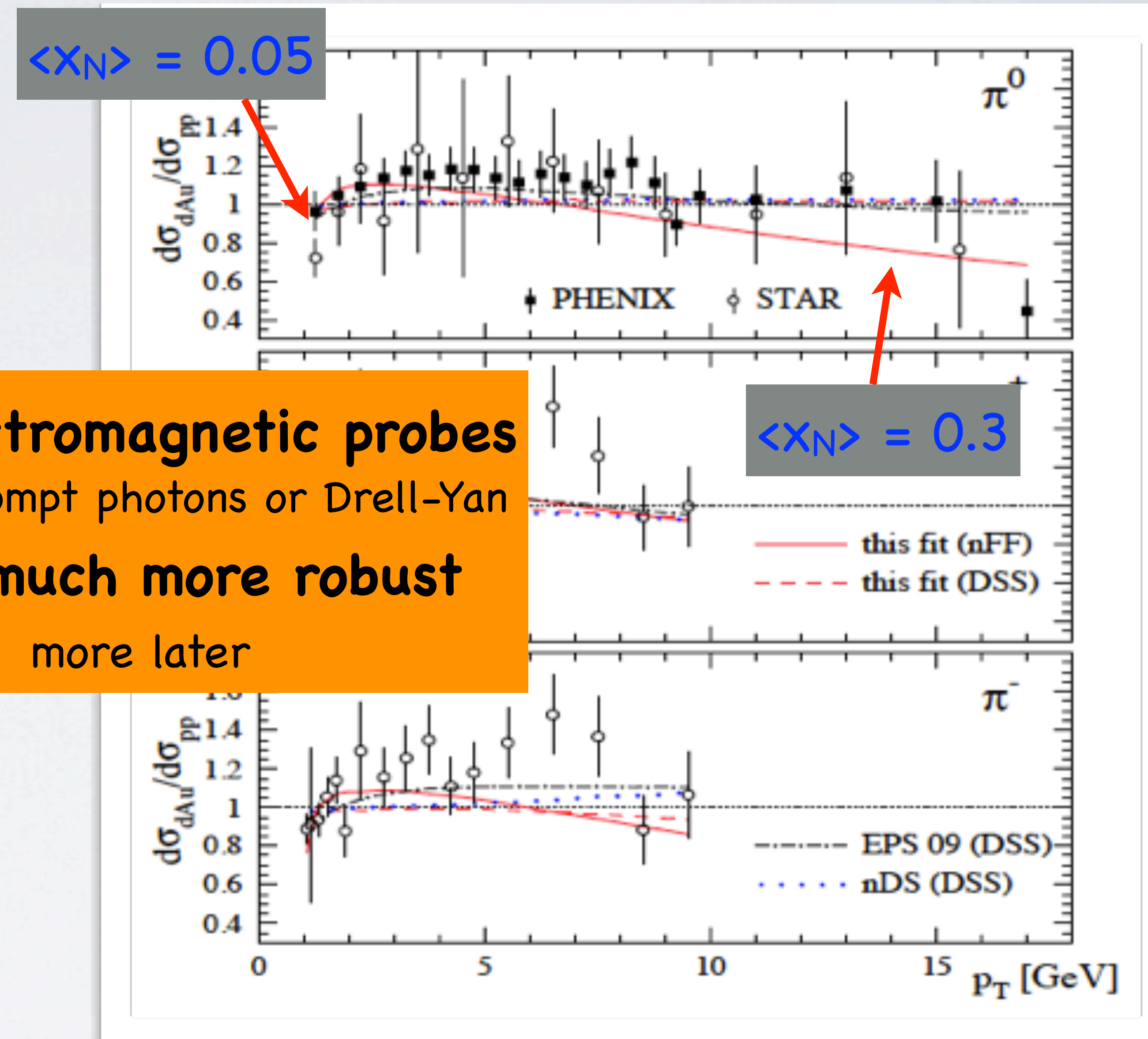

rare electromagnetic probes
such as prompt photons or Drell-Yan
are a much more robust
more later

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why interesting

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- gets one closer to the region where one expects saturation effects

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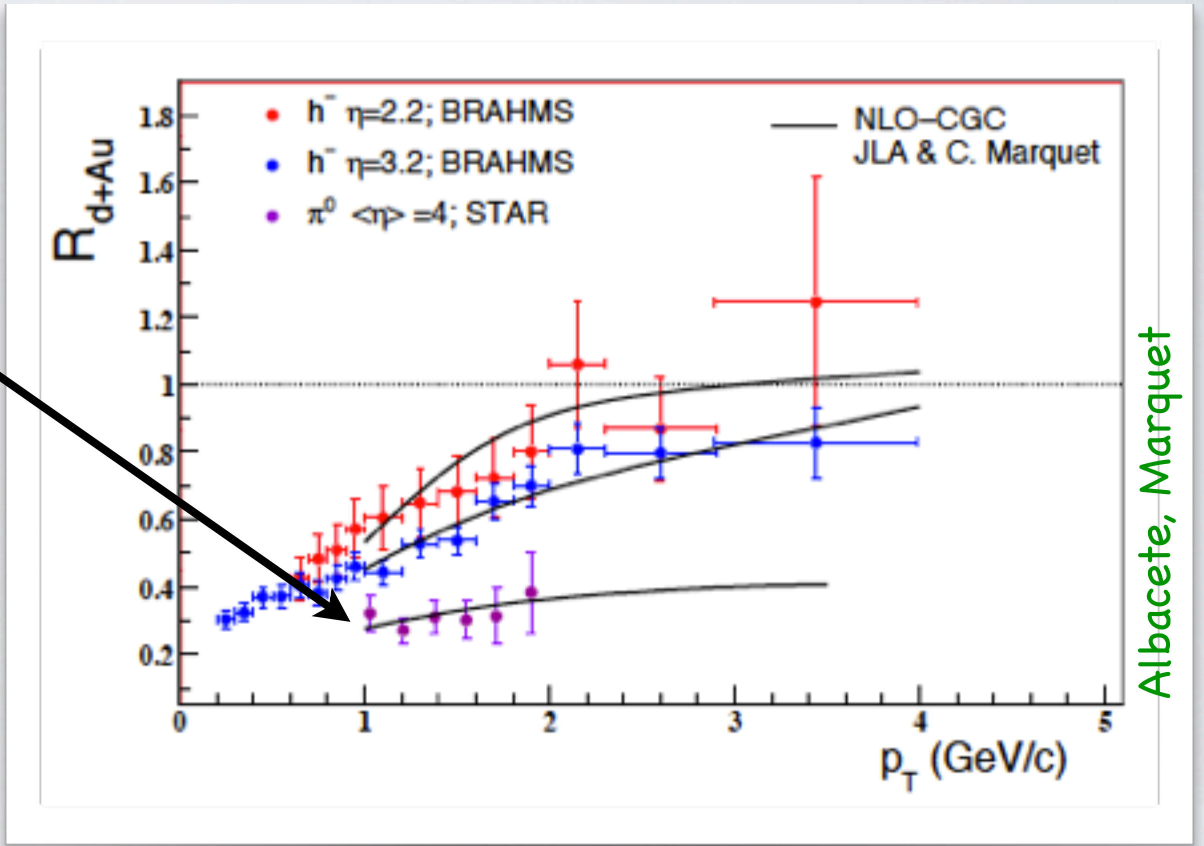
forward suppression well described within **non-linear rcBK evolution** (CGC)



Albacete, Marquet

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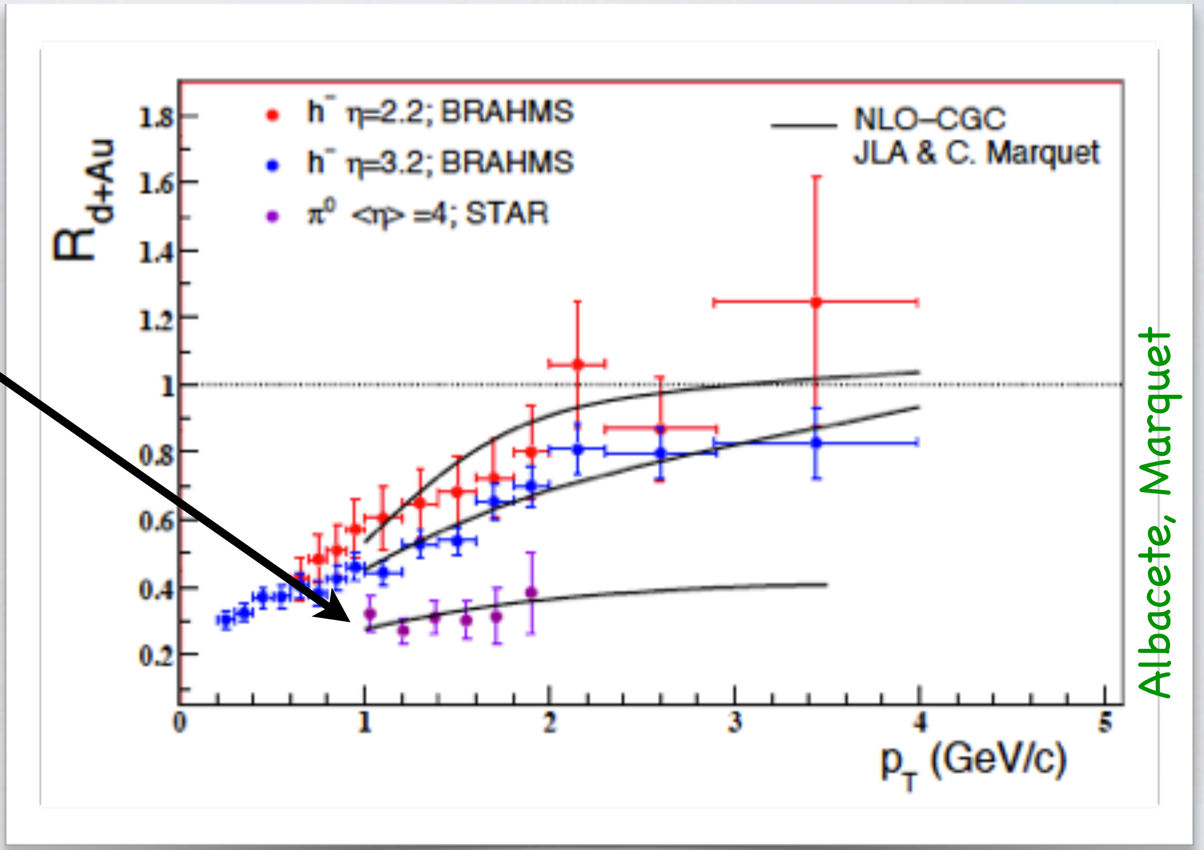

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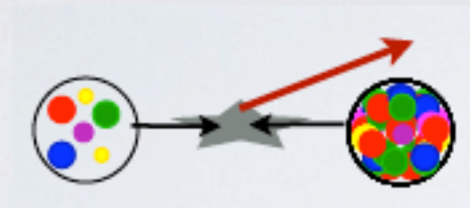

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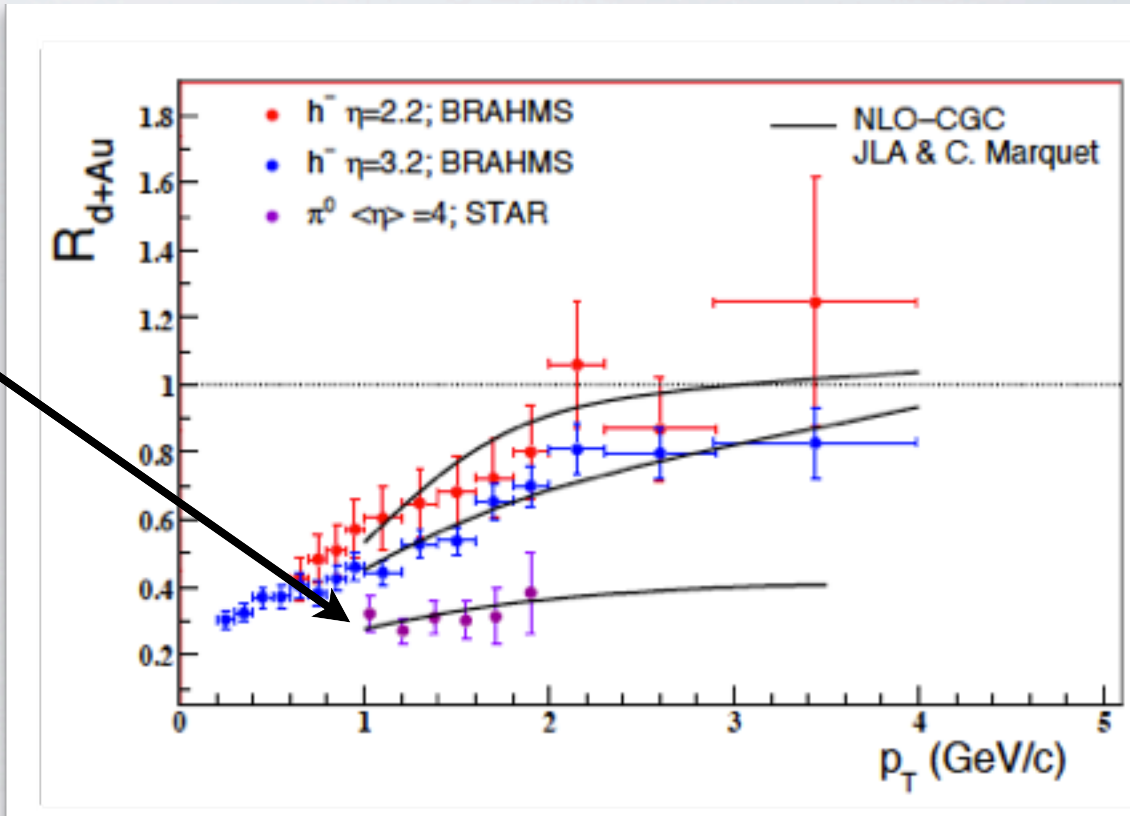

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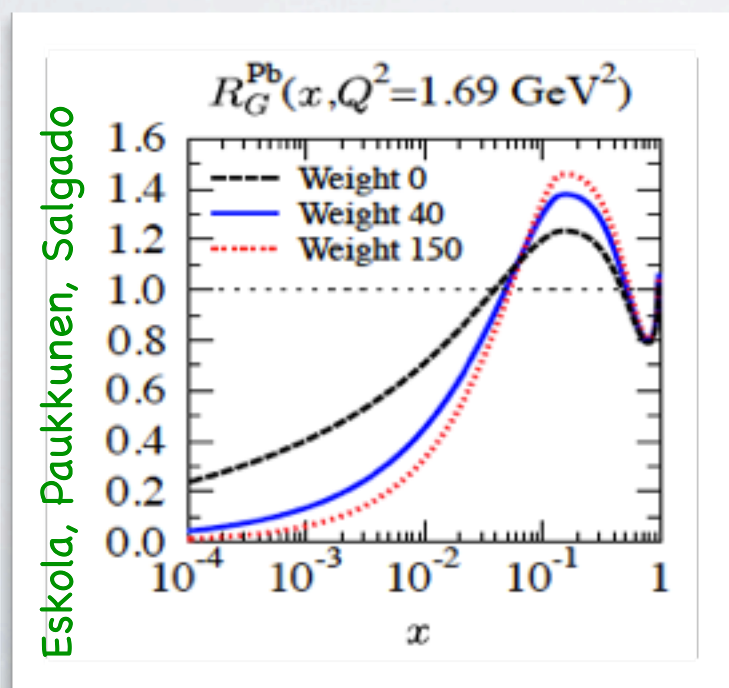

Eskola, Paukkunen, Salgado

- need humongous shadowing at a scale of about 1 GeV

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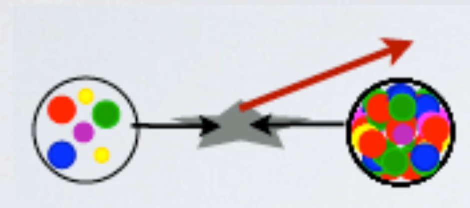

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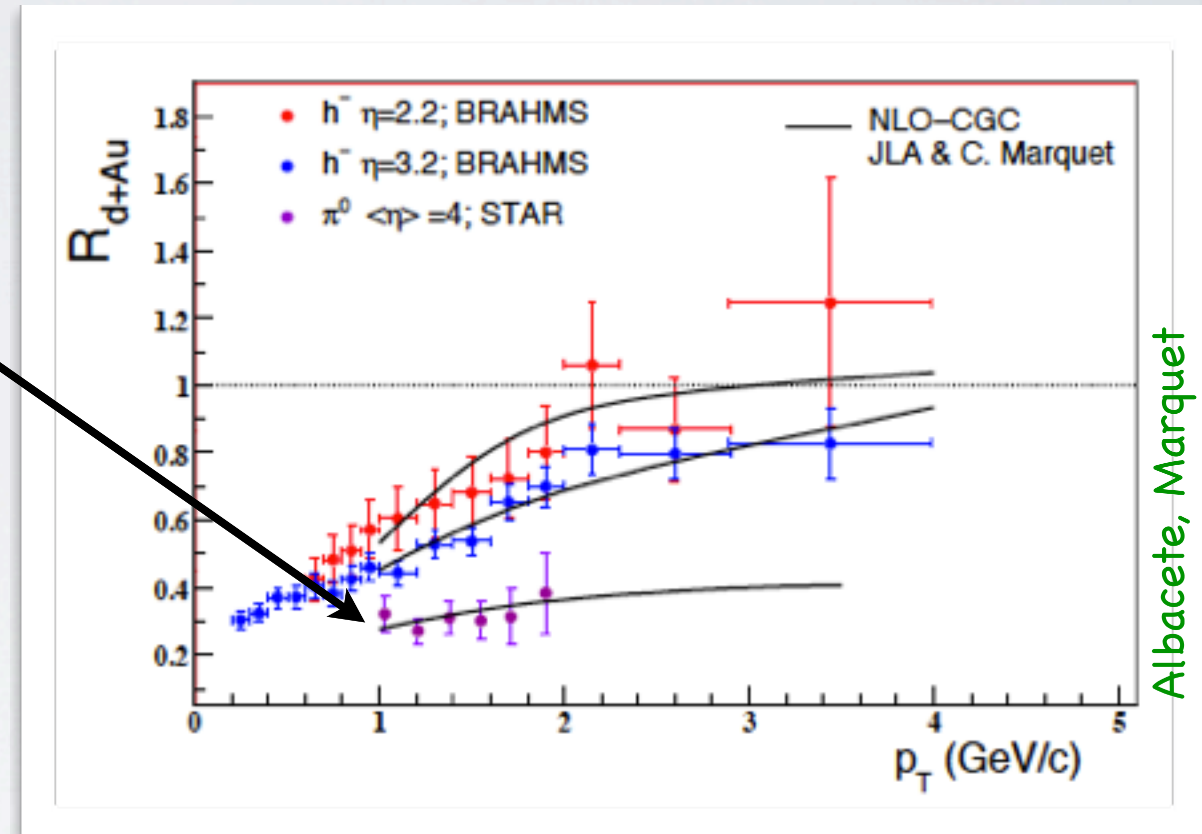

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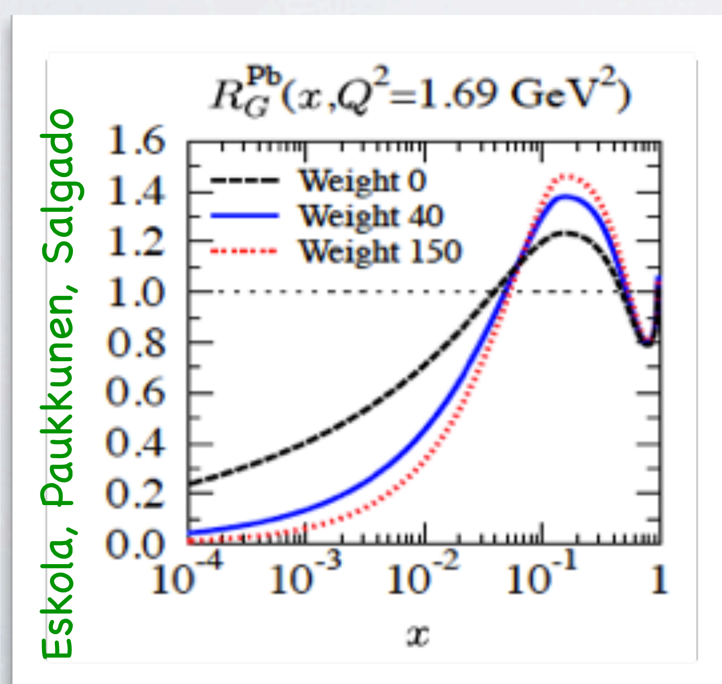
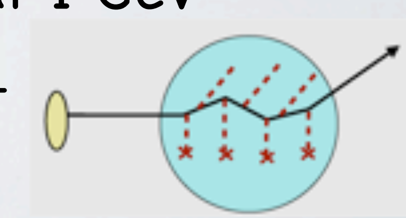


- need humongous shadowing at a scale of about 1 GeV

⚠ could be much less if final-state effects are relevant
advocated by Frankfurt, Strikman; Kopeliovich; ...



pions in dAu at forward rapidity

why interesting

- allows to access smaller
- gets one closer to the re
  one expects saturation e

$$\mathbf{x_{1,2} \simeq \frac{p_T}{\sqrt{s}} e^{\pm y}}$$

data indicate strong supp
of gluons at small x and lo

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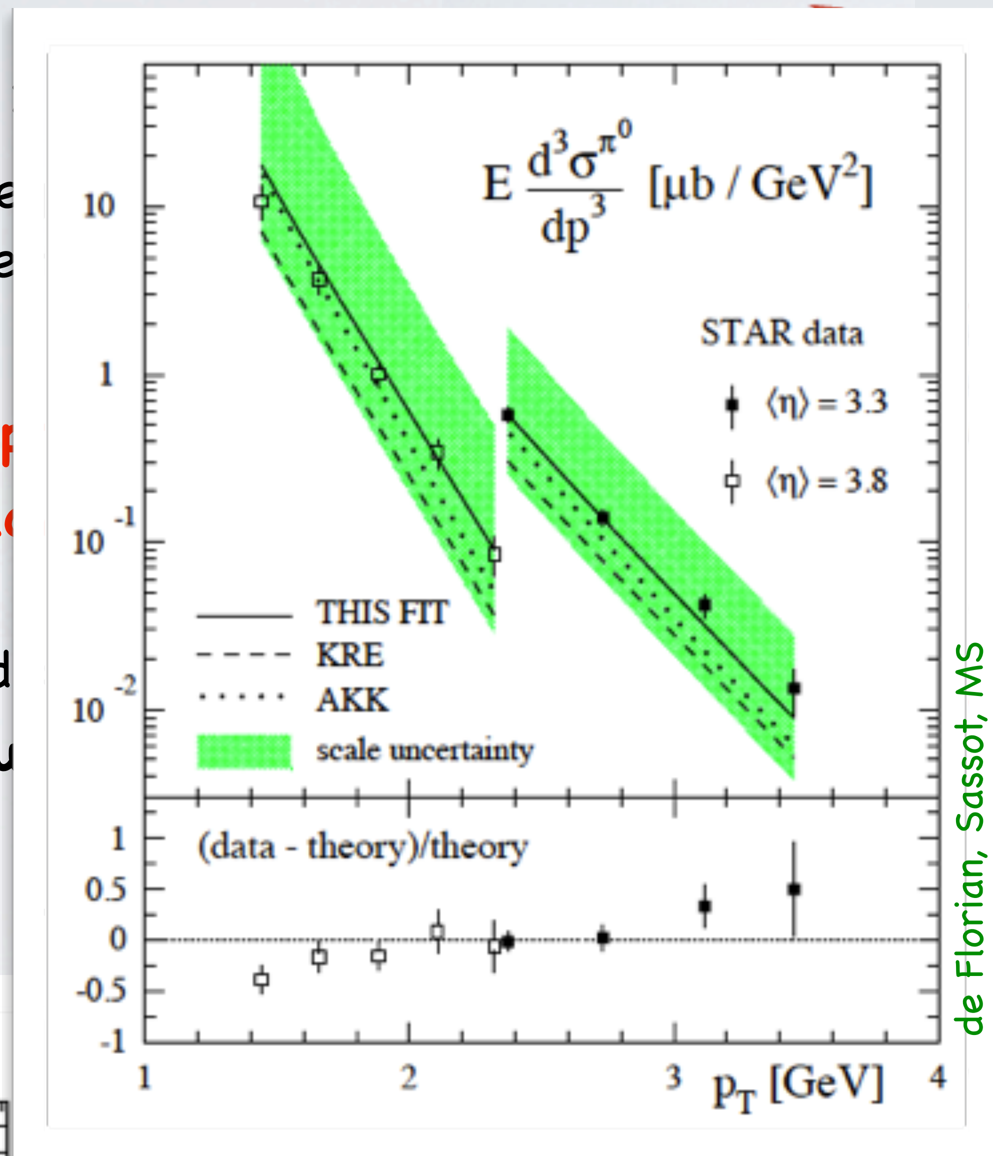

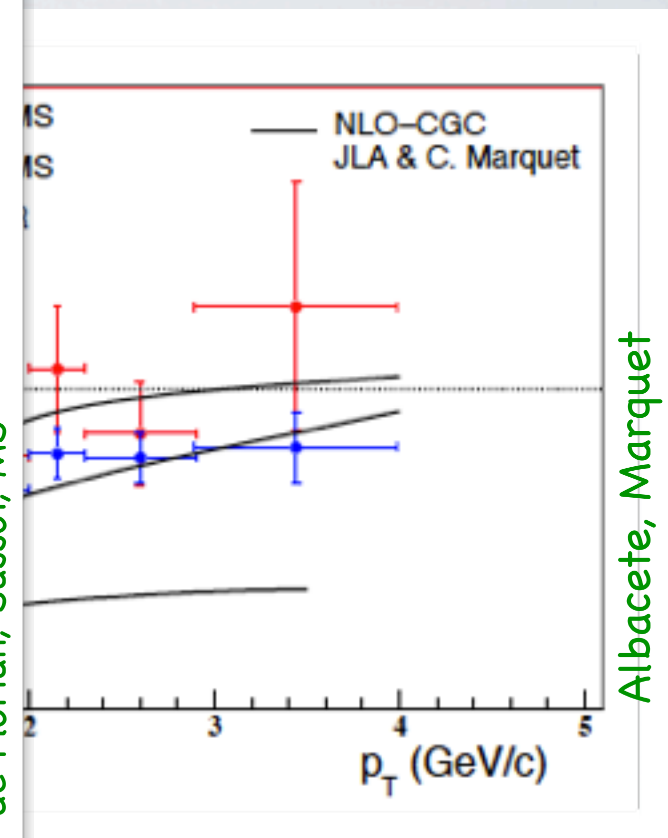

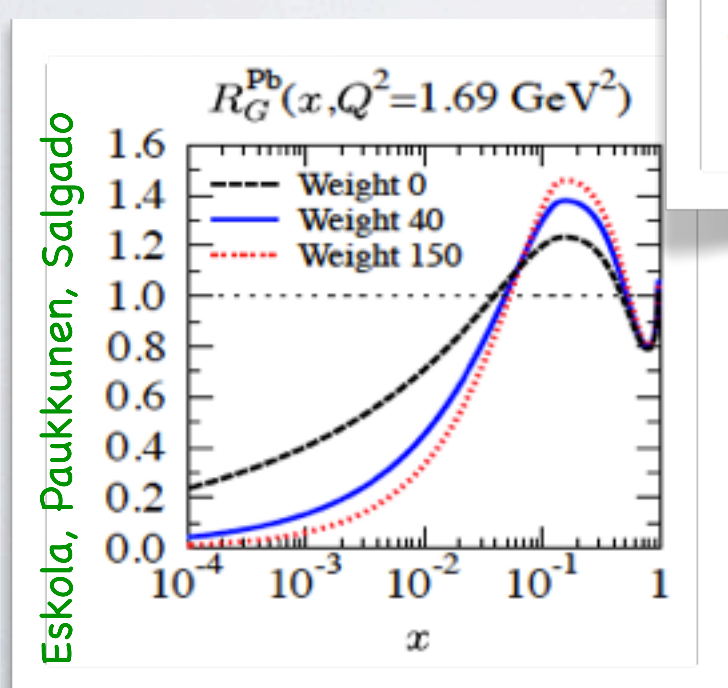

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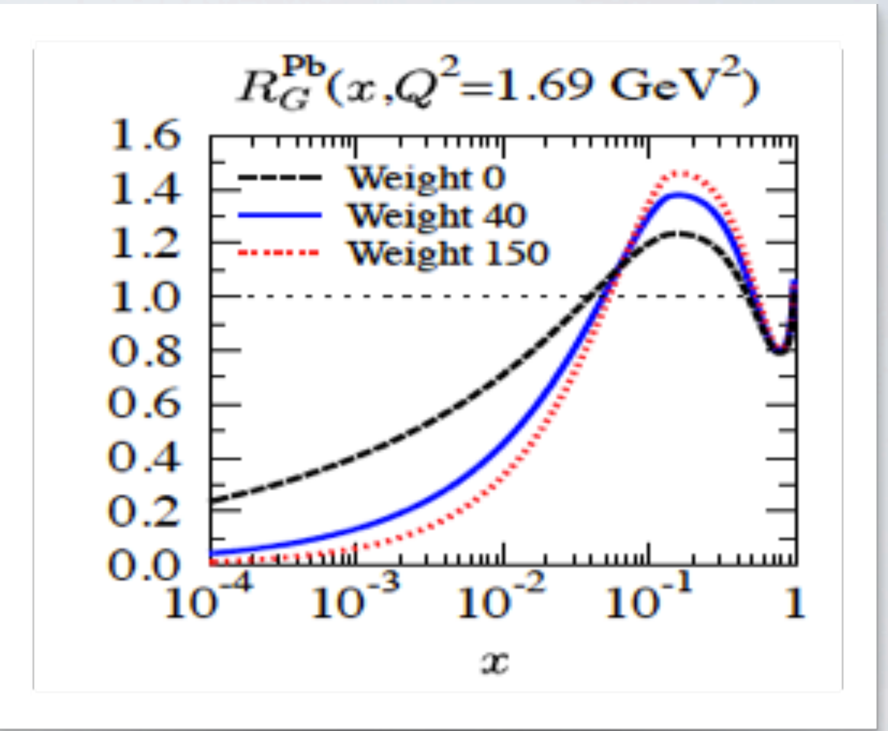
⚠ pQCD does not work well at small p_T and large y
corrections become excessive; pp data for y=4 not used in any fit

general issue with pQCD and forward physics at RHIC
recall: CGC has Q_S as additional semi-hard scale

how "bad" are extreme initial conditions?

we refrain from using the forward dAu data in our analysis ...

... however, there is enough freedom at small x to enforce a good description at the expense of strong shadowing



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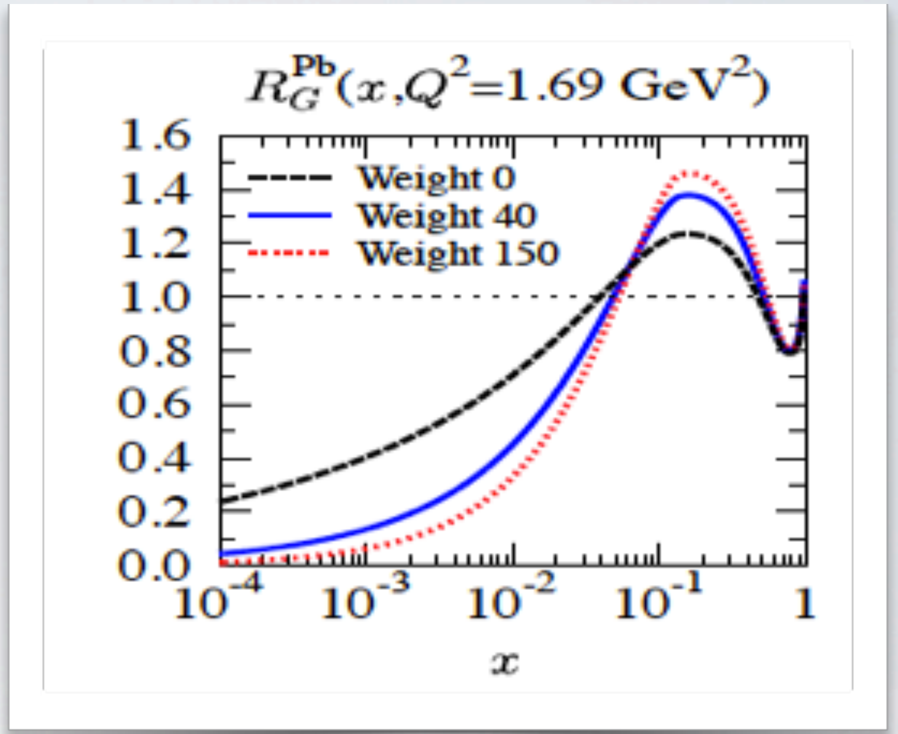

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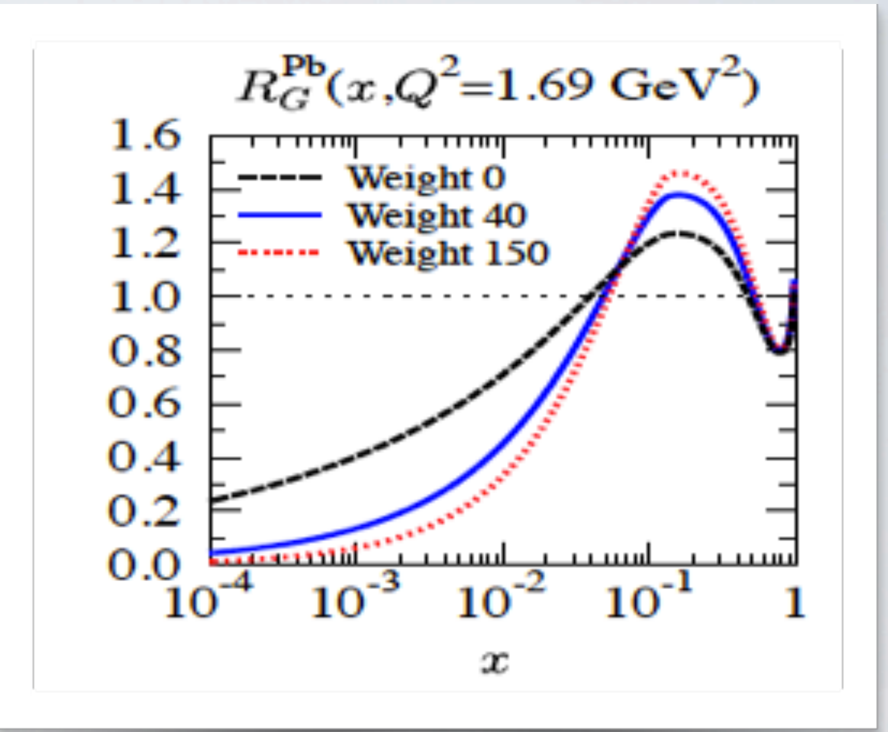

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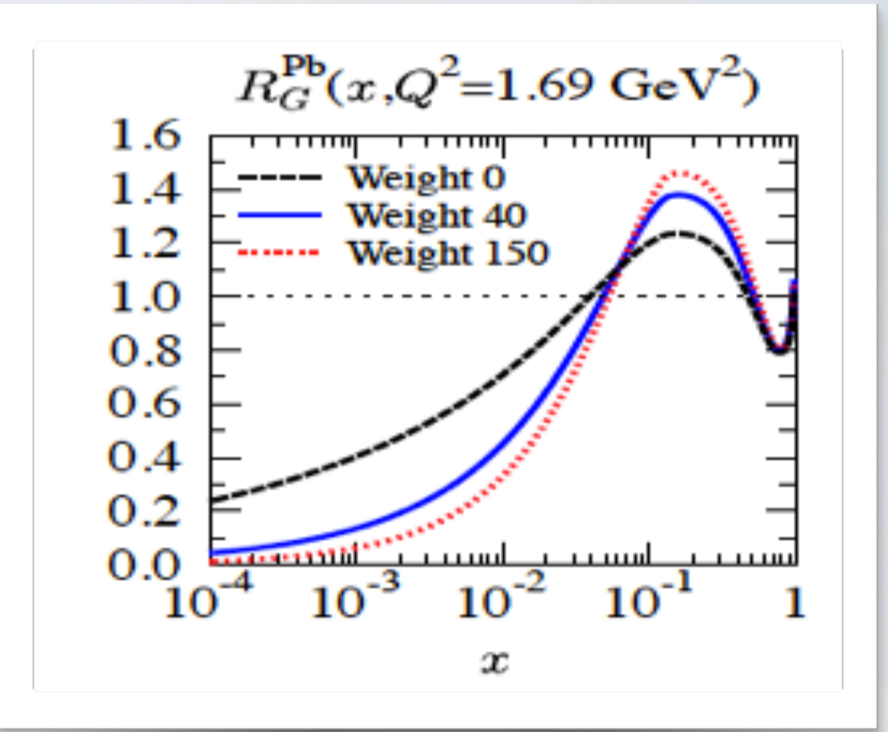

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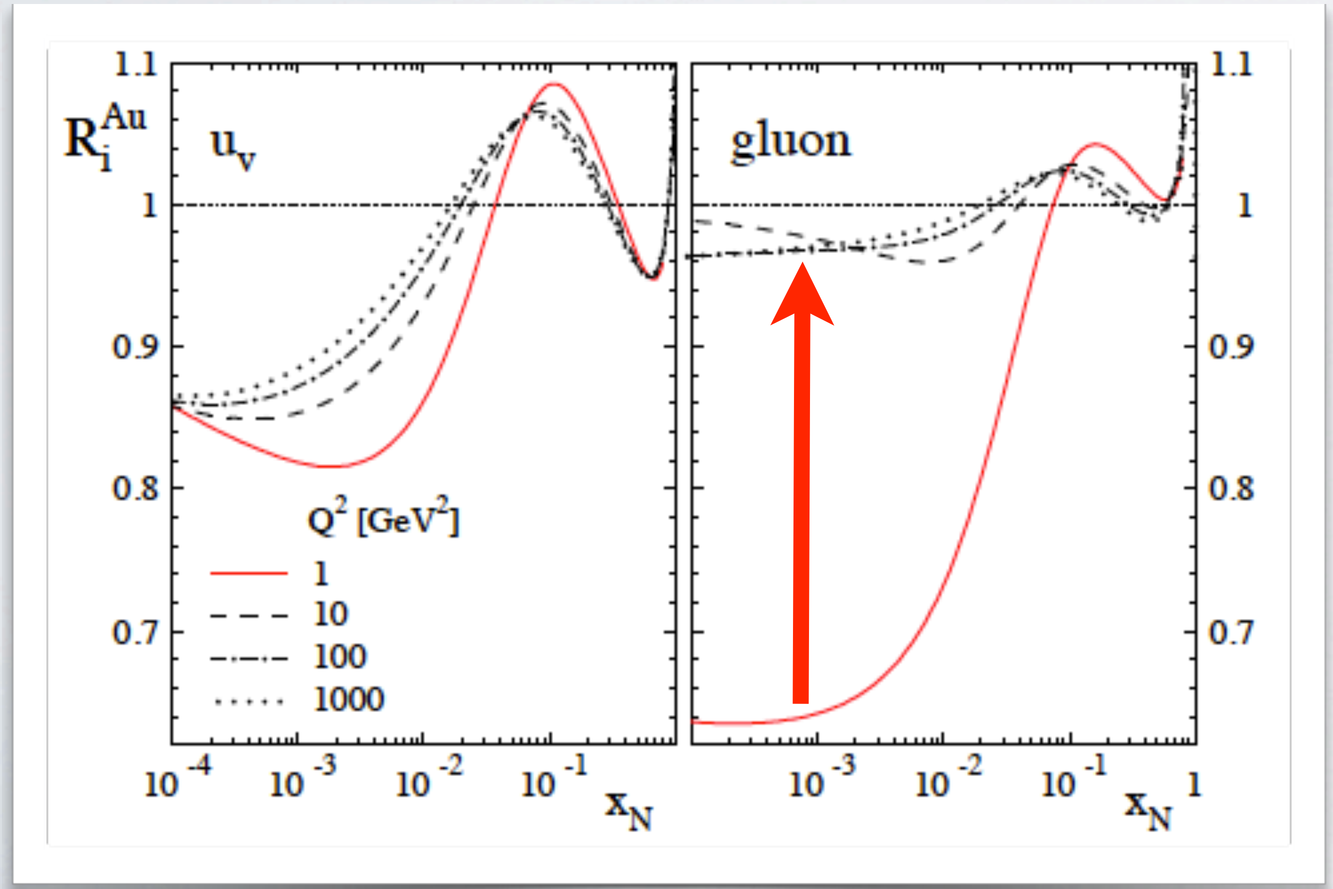

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a strong shadowing of the gluon would quickly evolve away

how about using nPDFs in AA collisions ?

many observables of interest involve

small p_T, global properties, centrality dependence, ….

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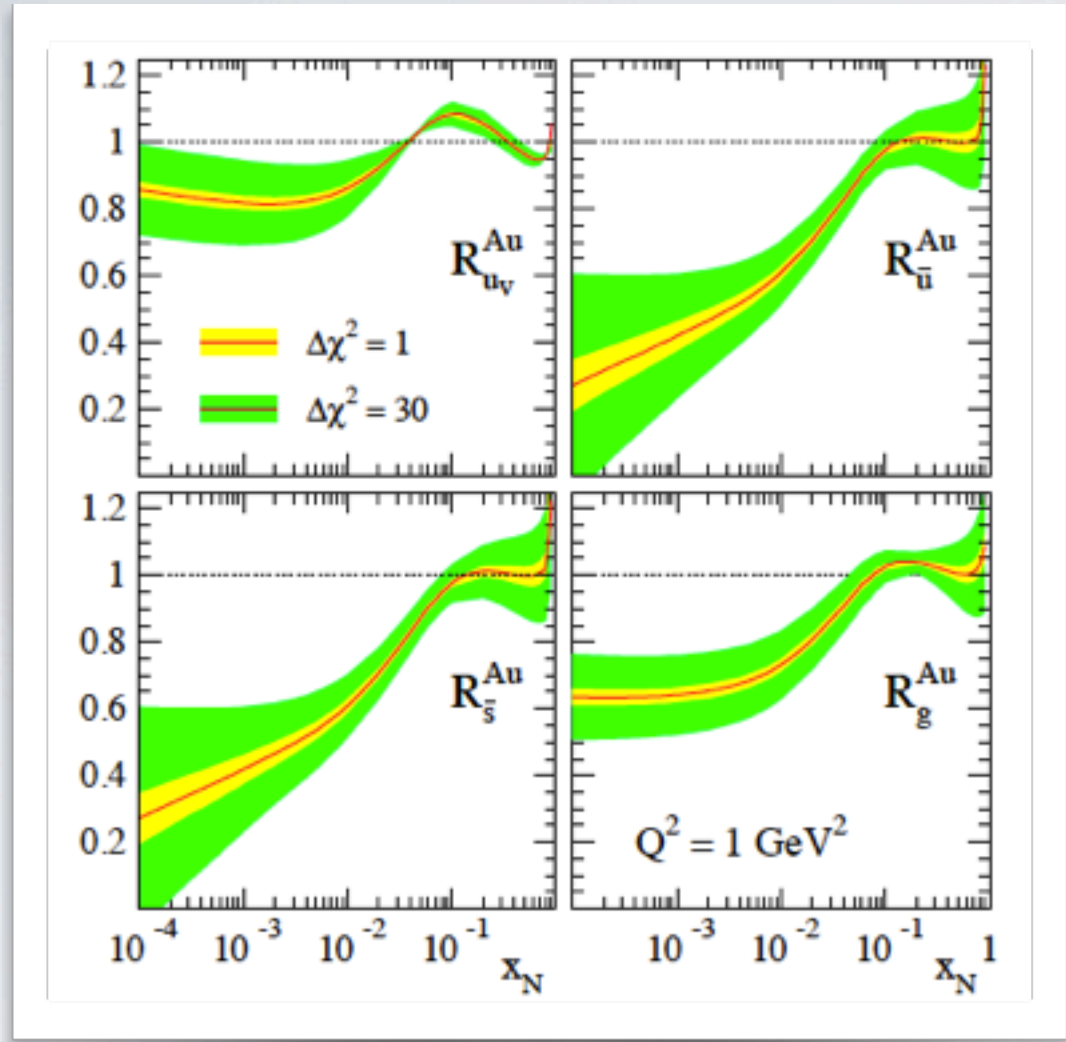
we do not touch AA data for the time being
nPDFs should be determined from probes in eA or pA
preferentially electromagnetic ones (free of hadronization issues)

DSSZ nPDFs and their uncertainties

uncertainties at input scale of 1 GeV (for gold nucleus)



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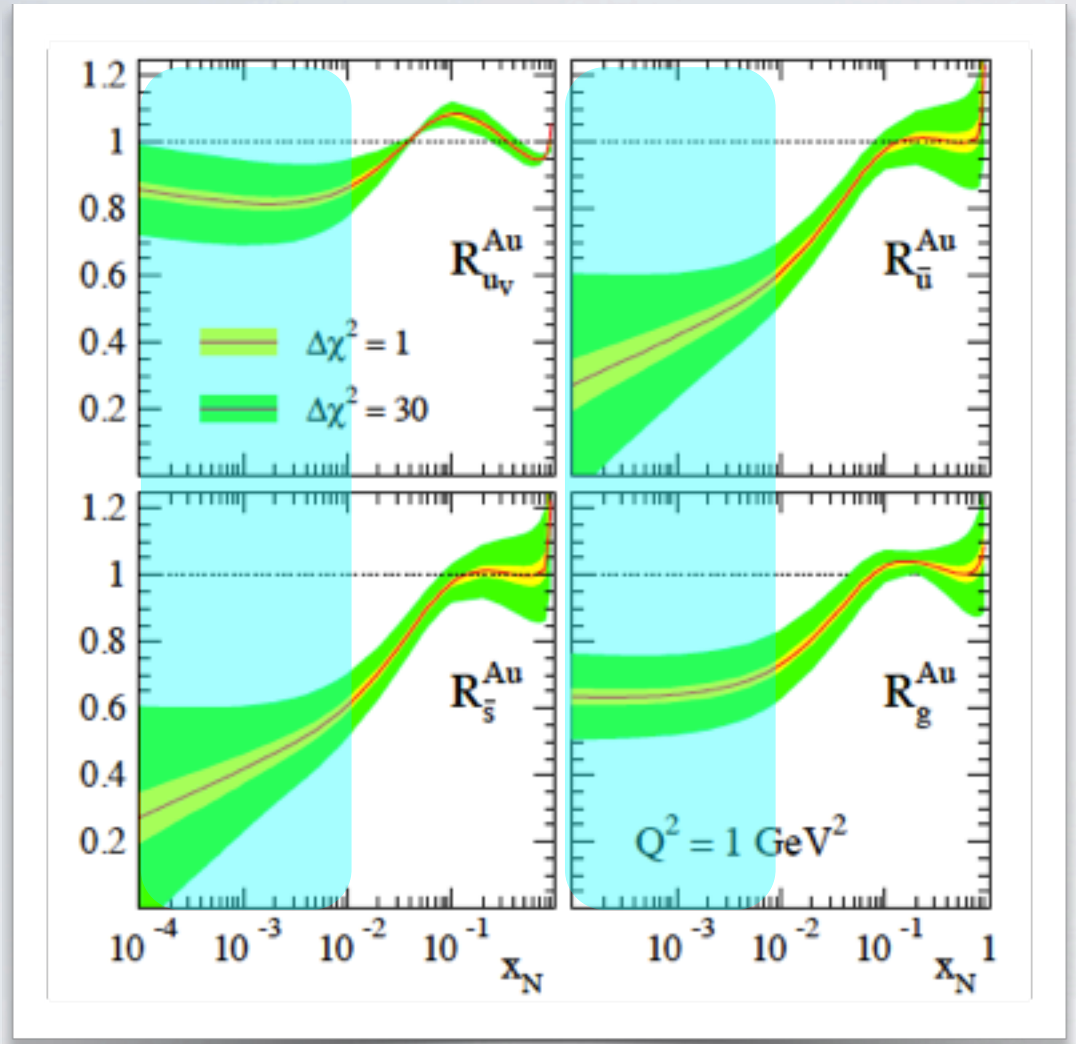

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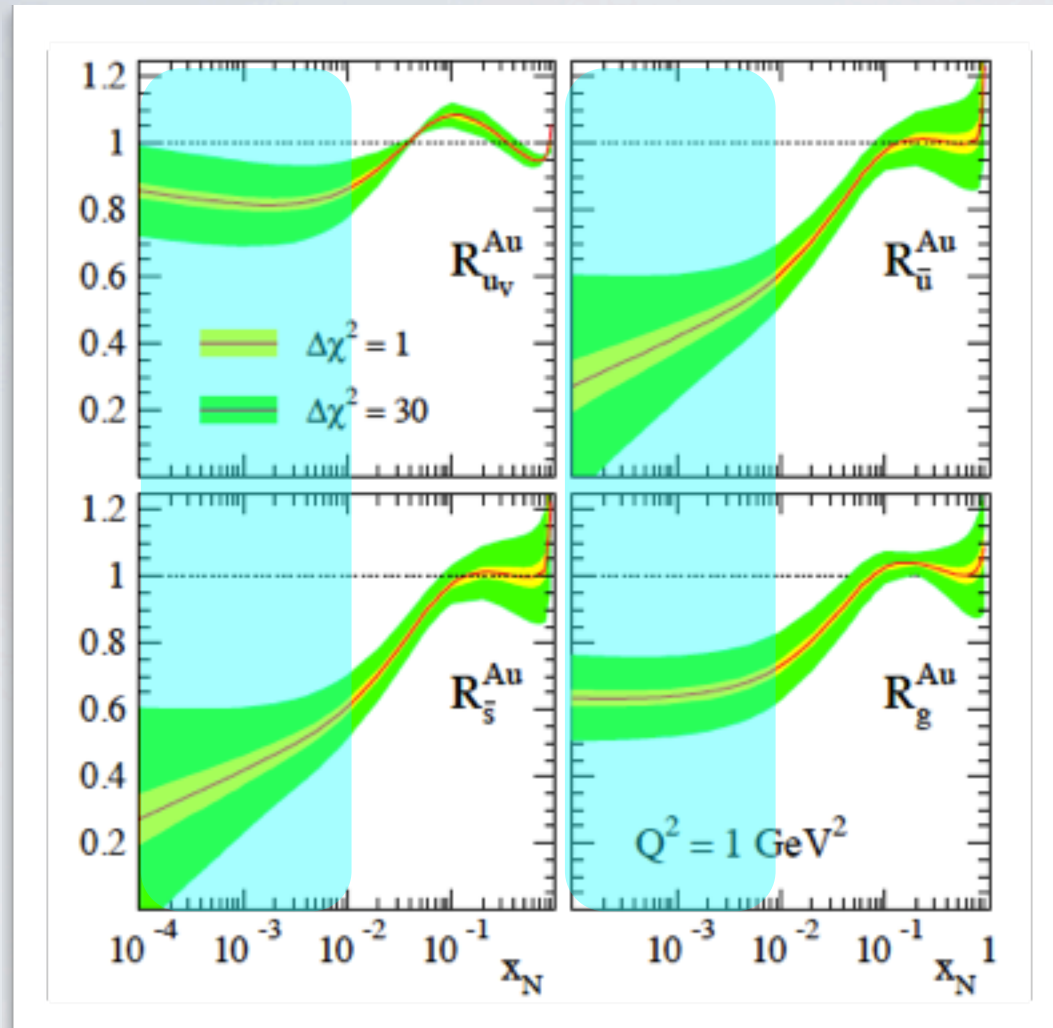

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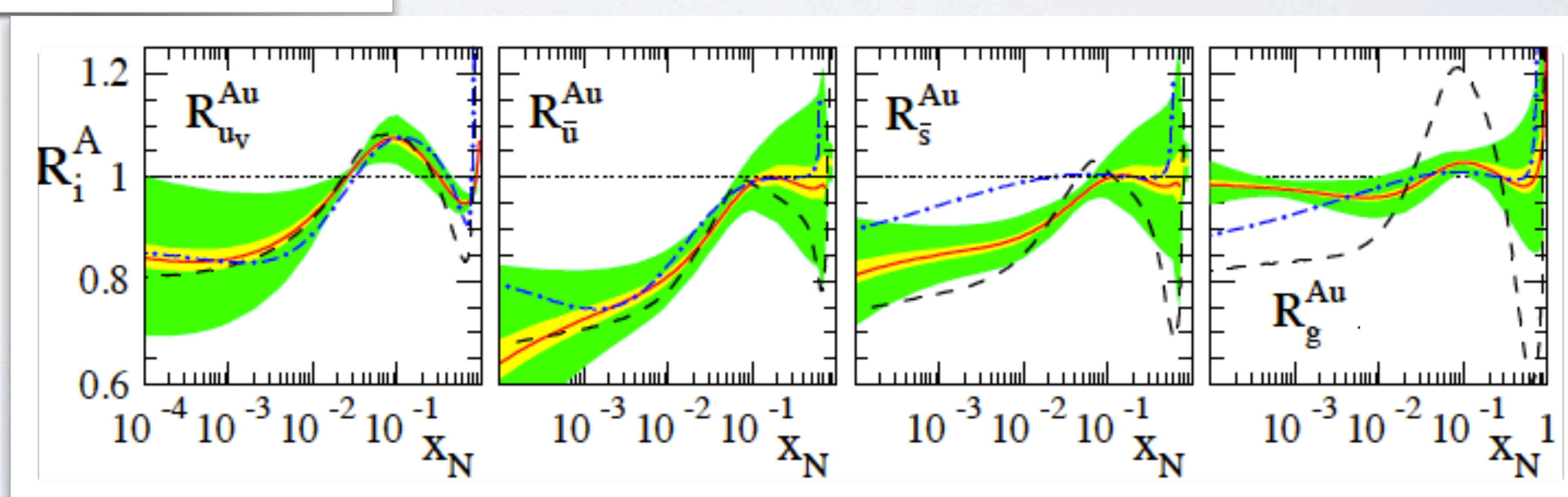
evolve to 10 GeV²



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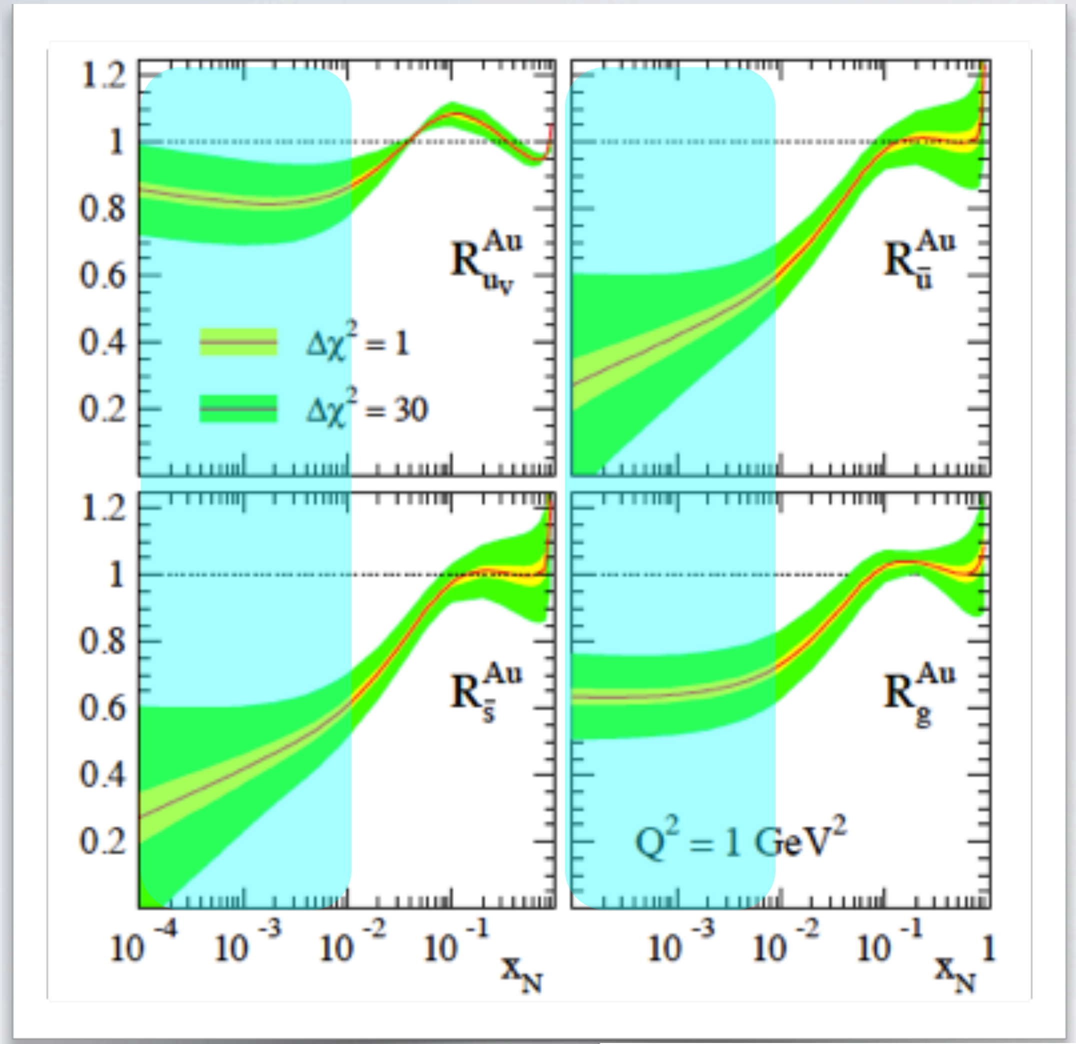

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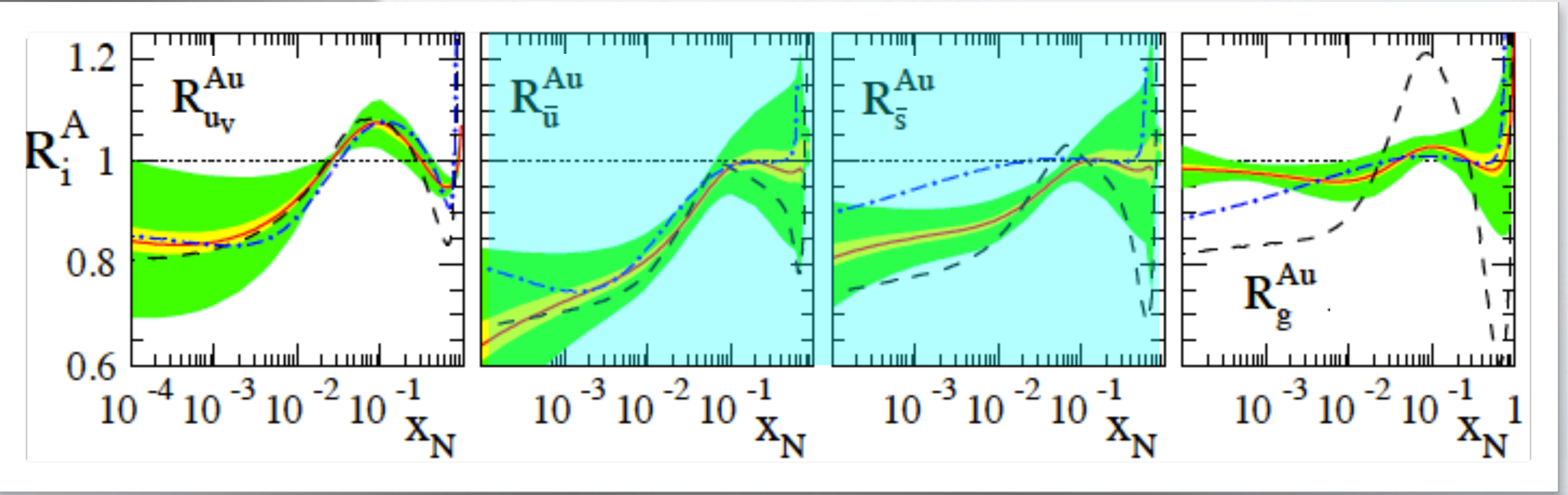

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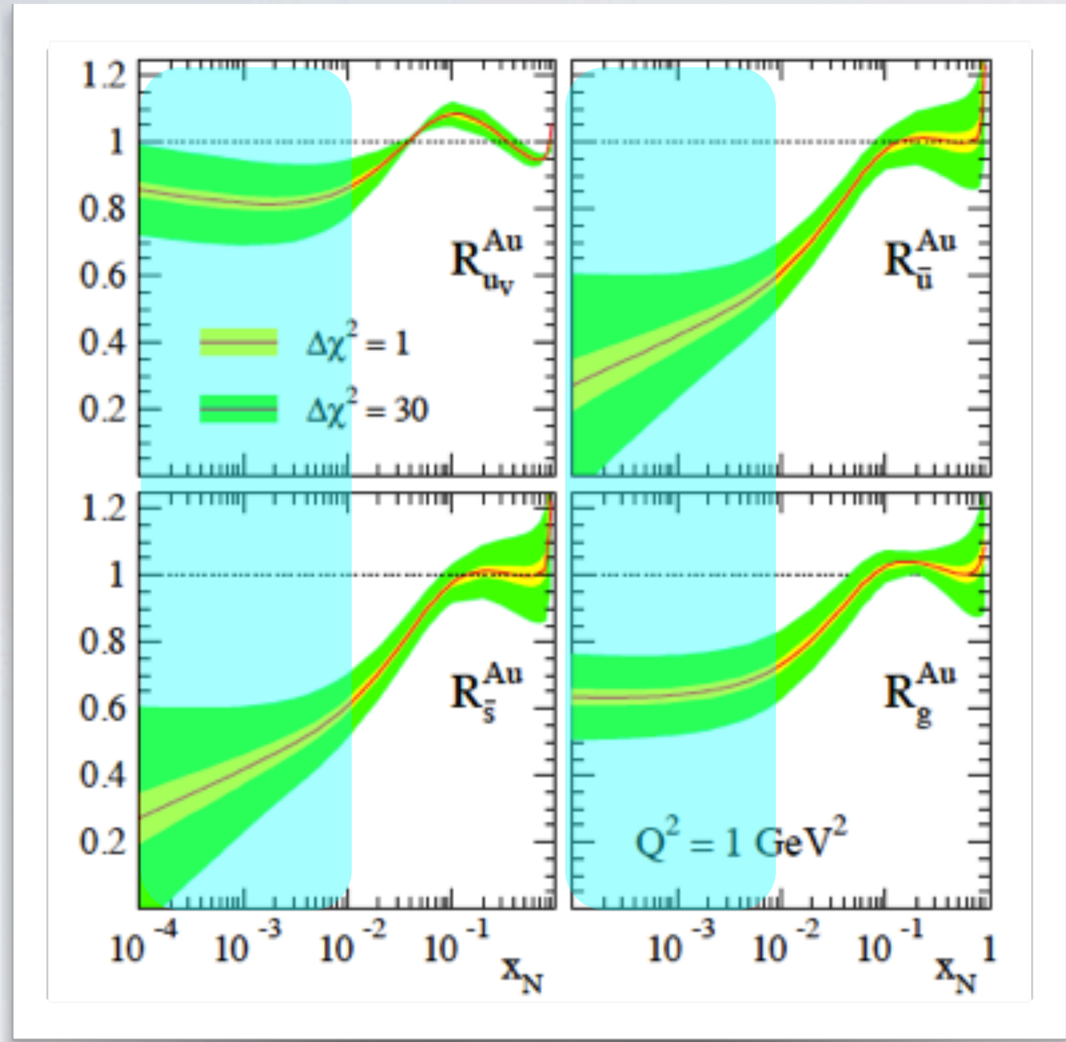

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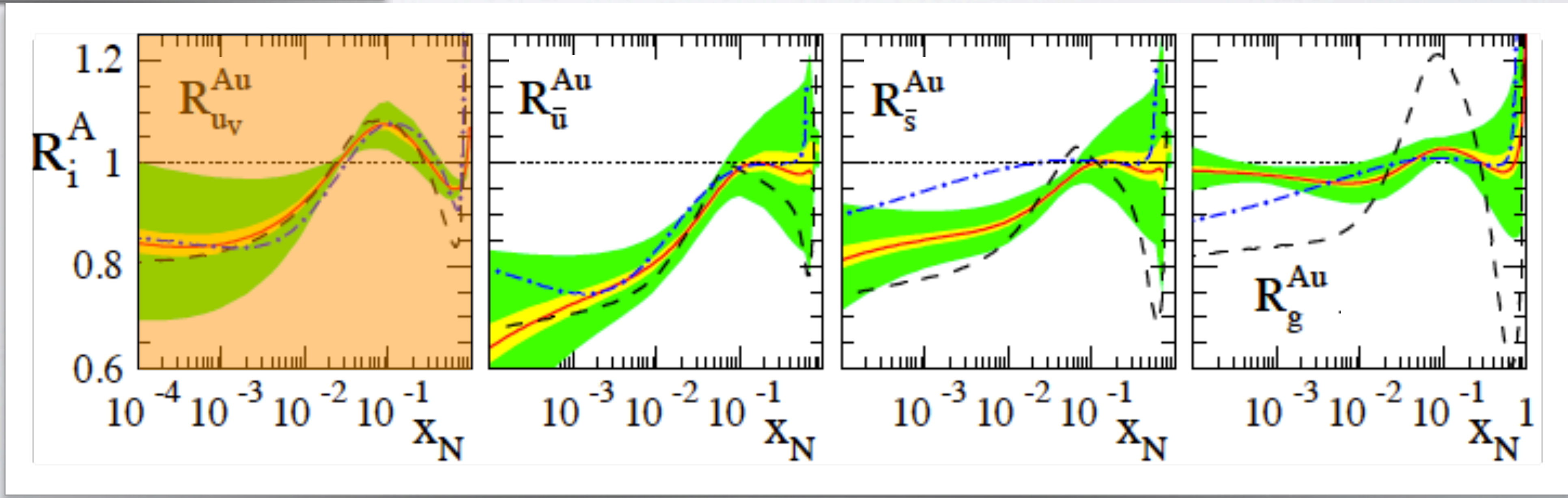

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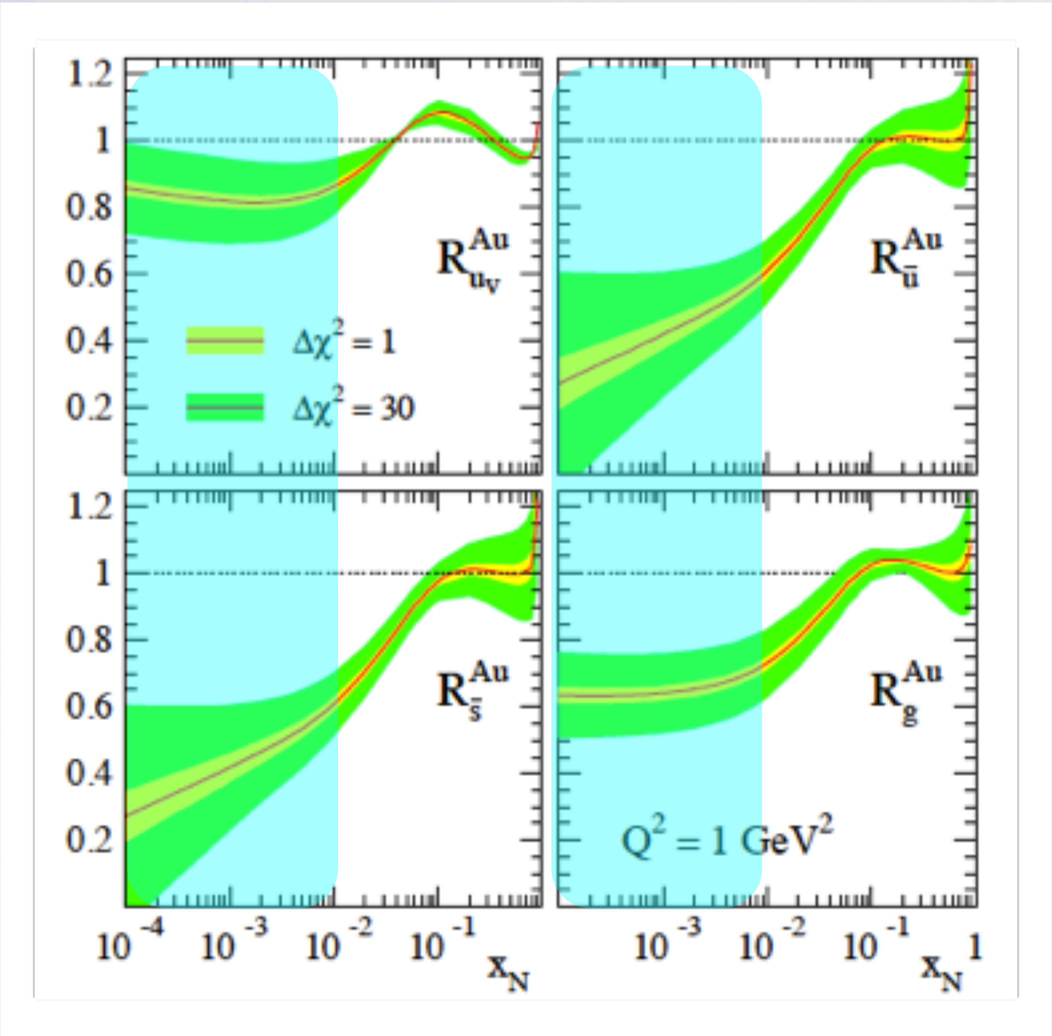

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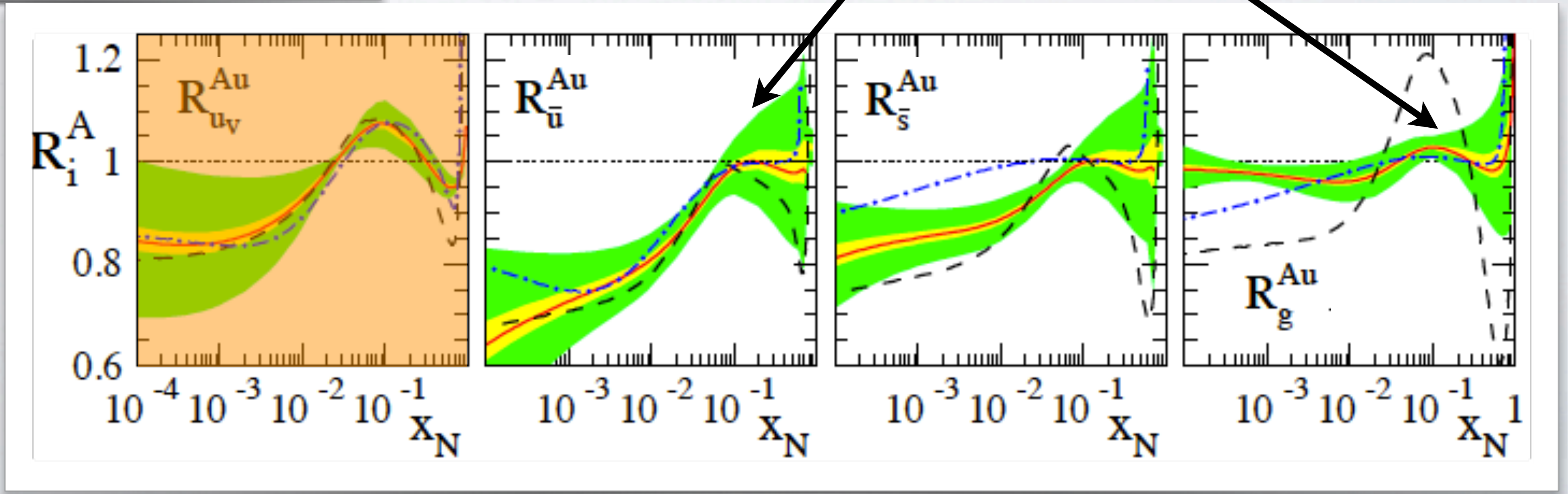
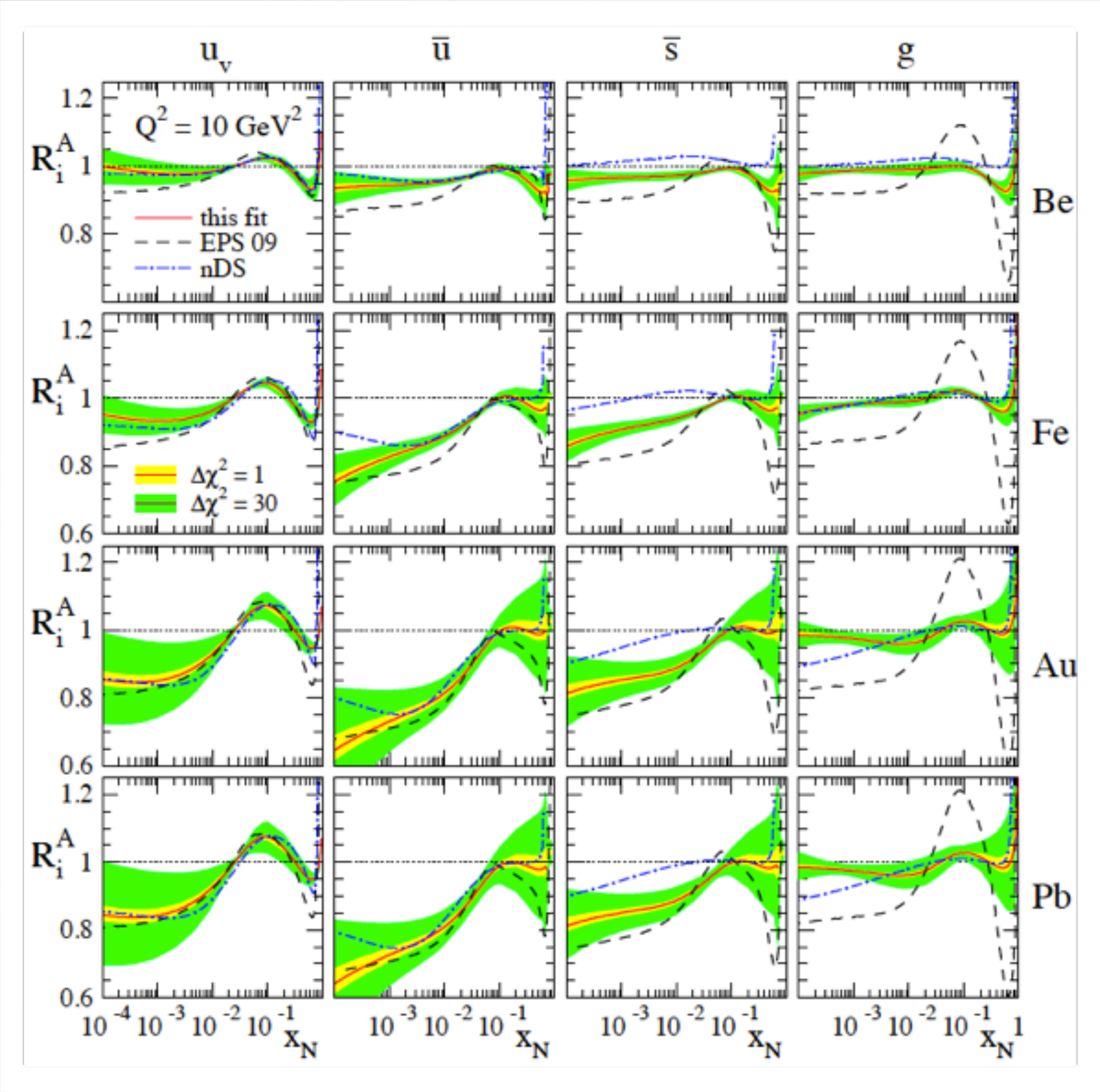
- little evidence for anti-shadowing in sea (and gluon)

evolve to 10 GeV^2



DSSZ nPDFs and their uncertainties

A dependence at Q^2 = 10 GeV^2



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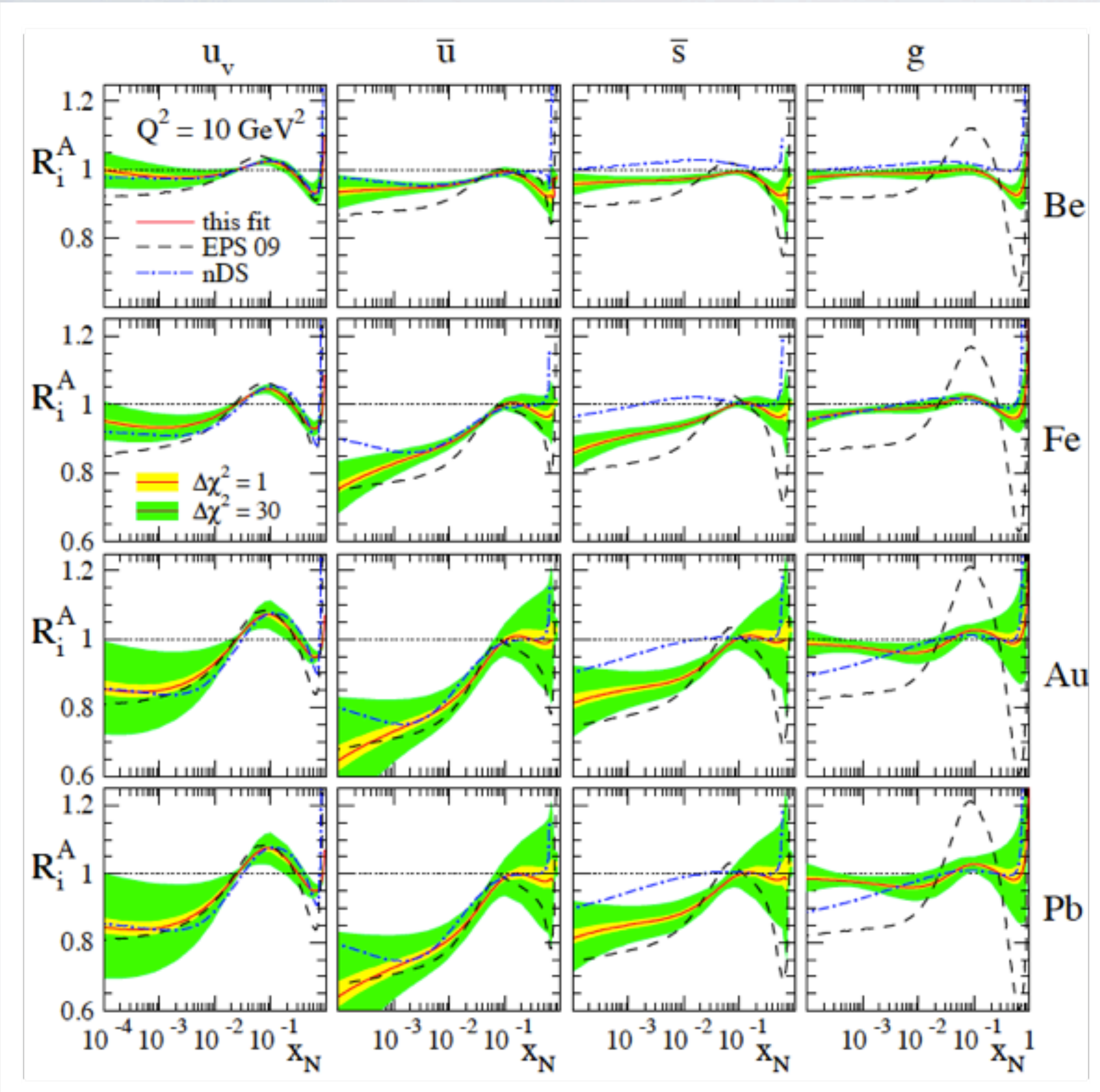

- nuclear modifications increase with A

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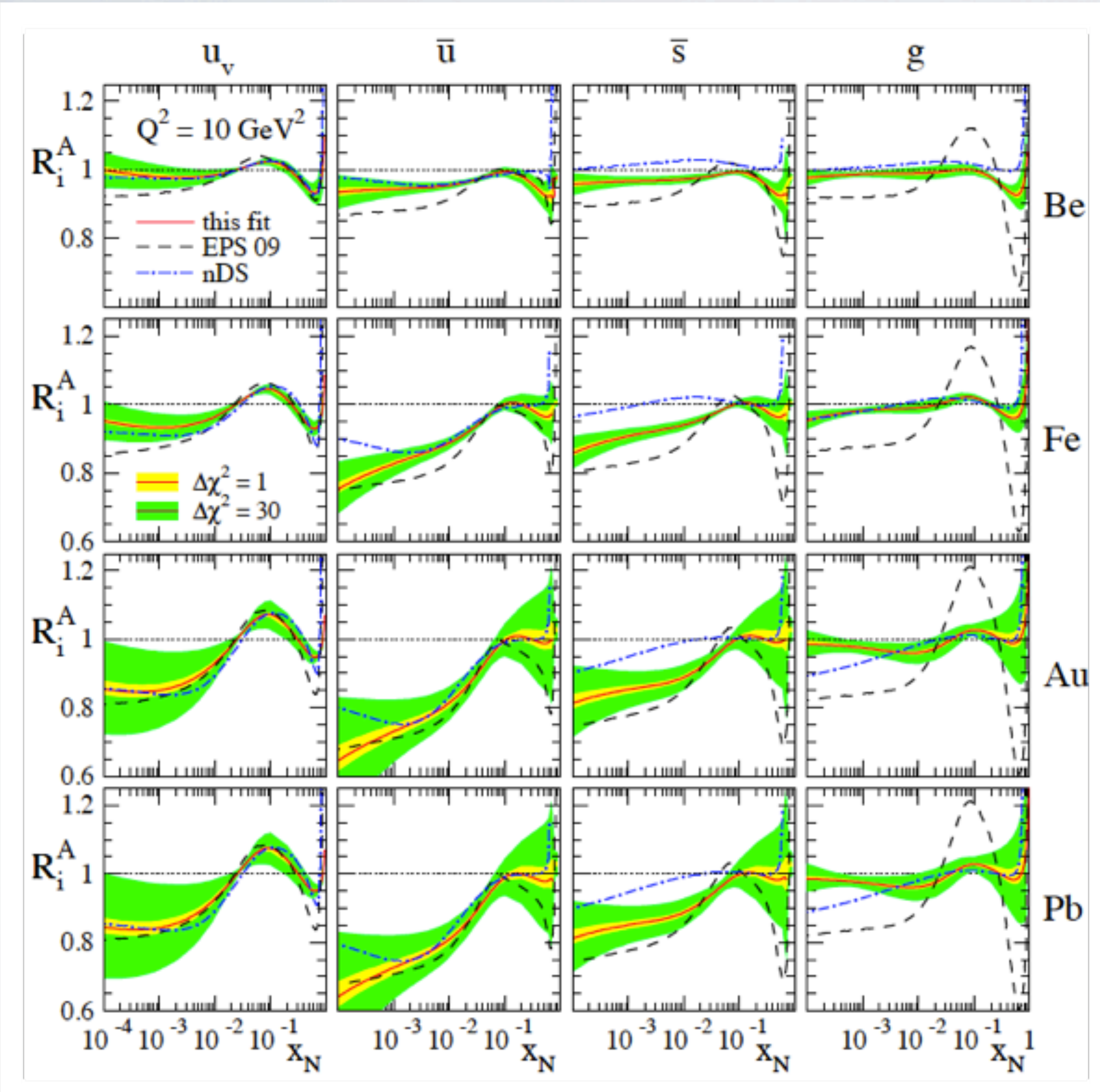

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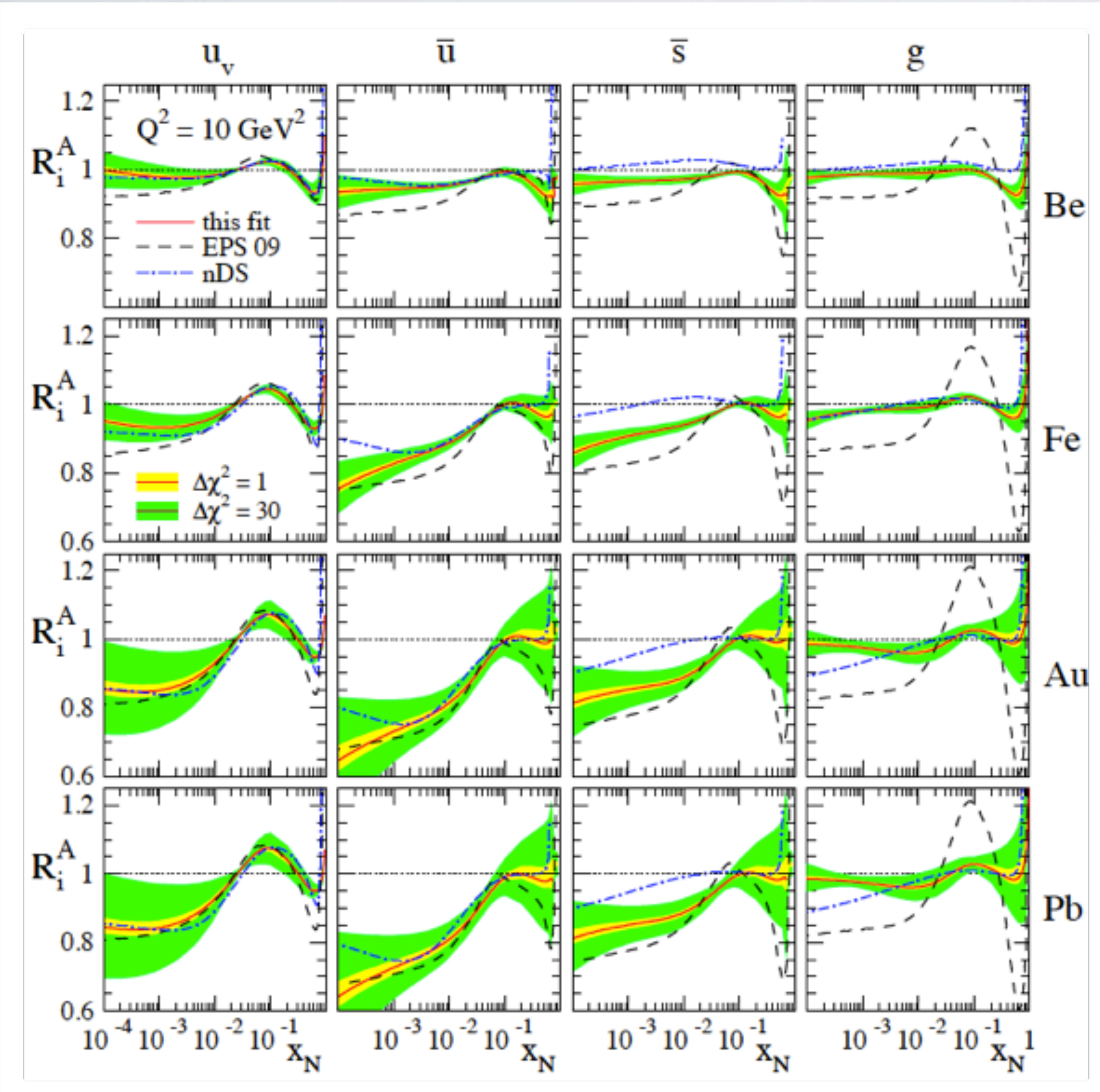

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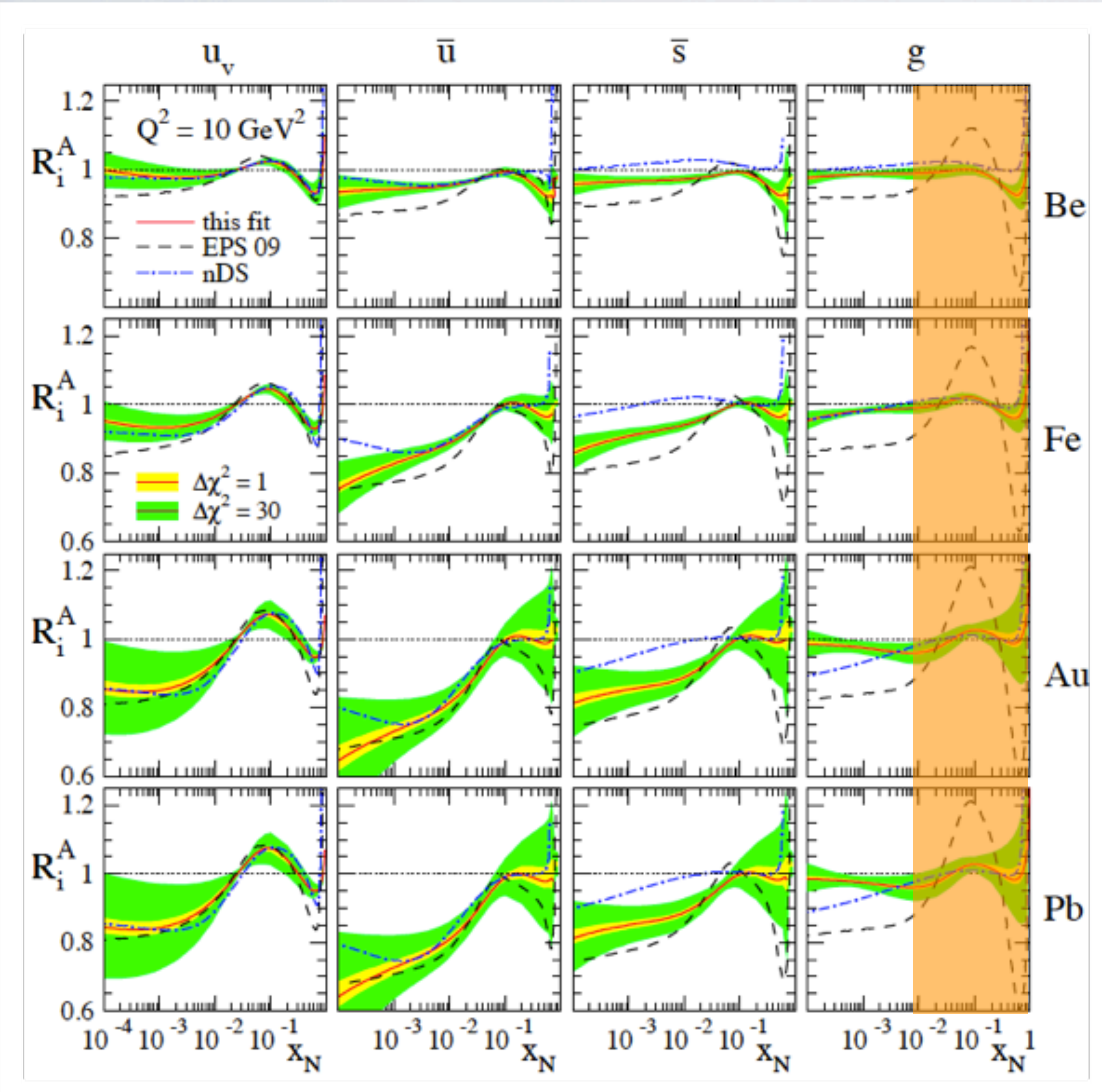

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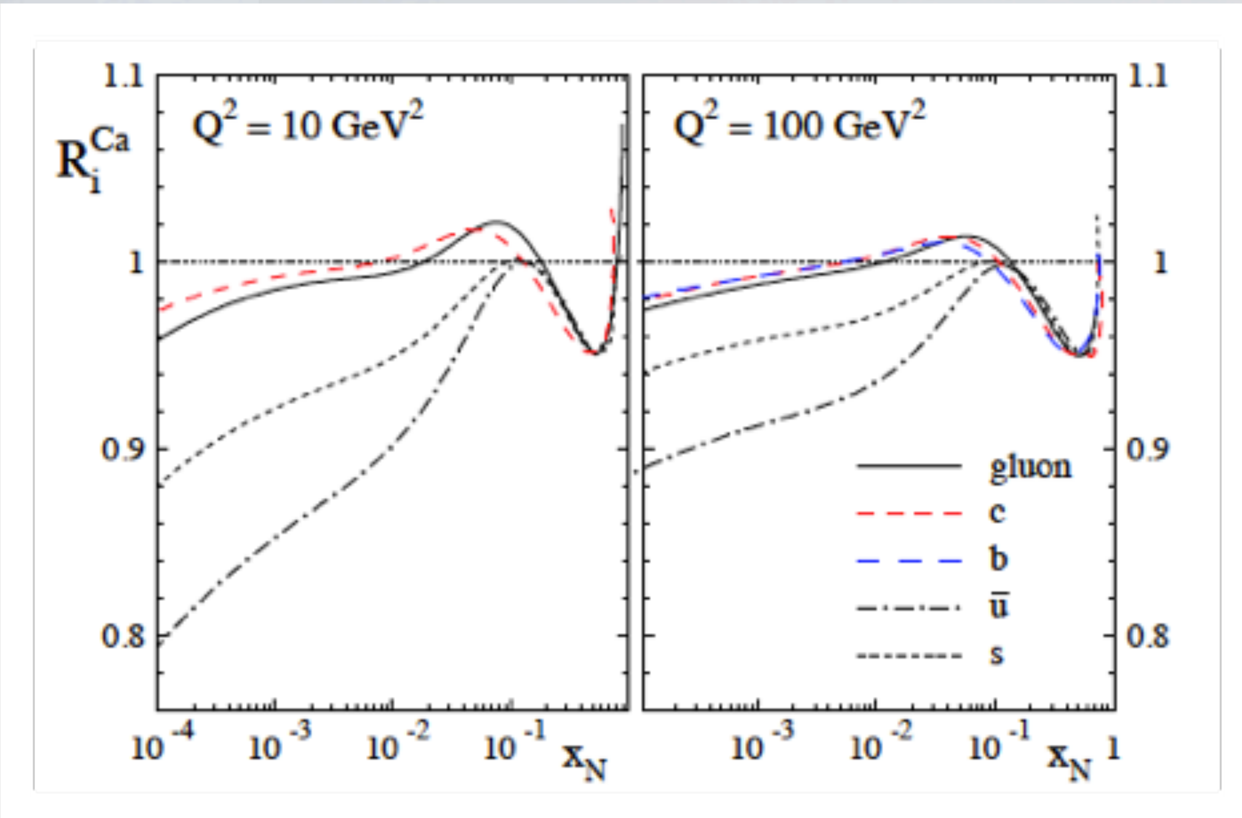
- **MUCH less anti-shadowing and EMC effect than for EPS gluon**

  driven by the way dAu data are analyzed

DSSZ nPDFs: peculiarities



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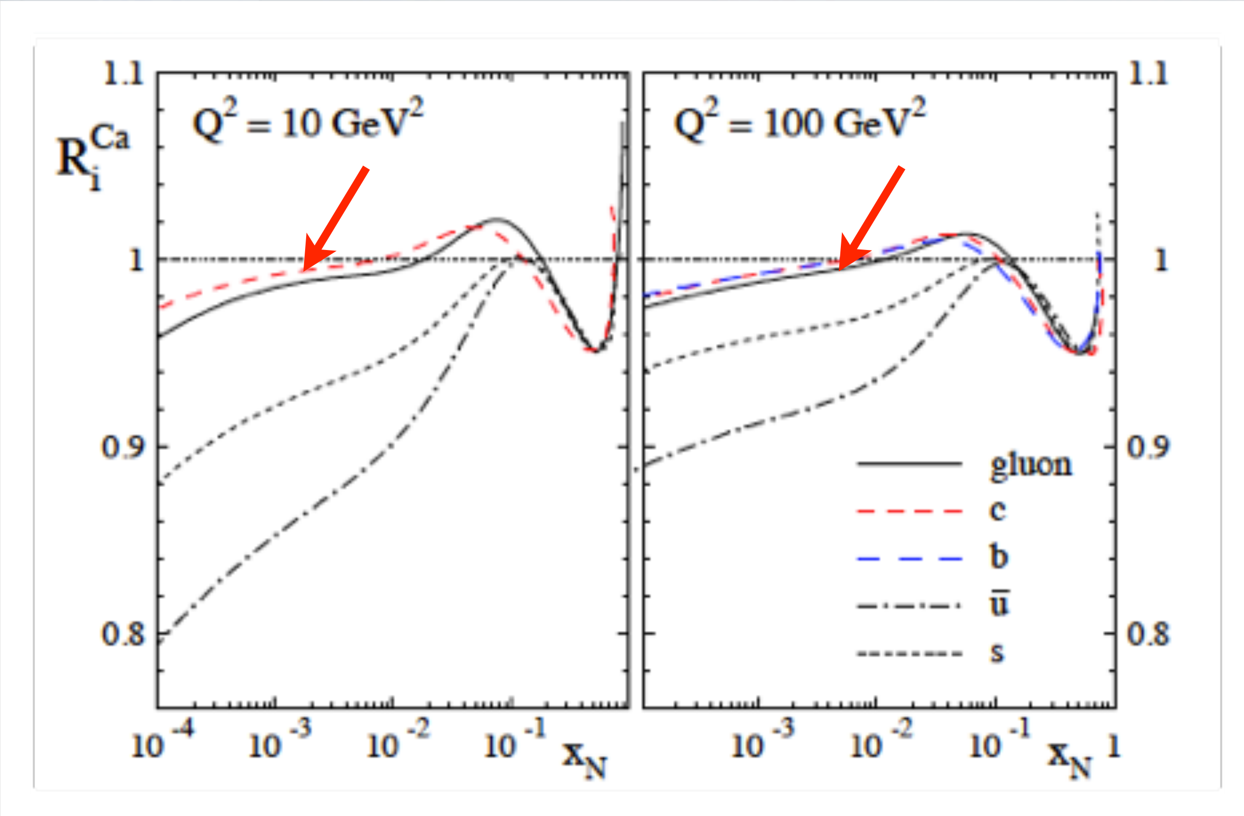

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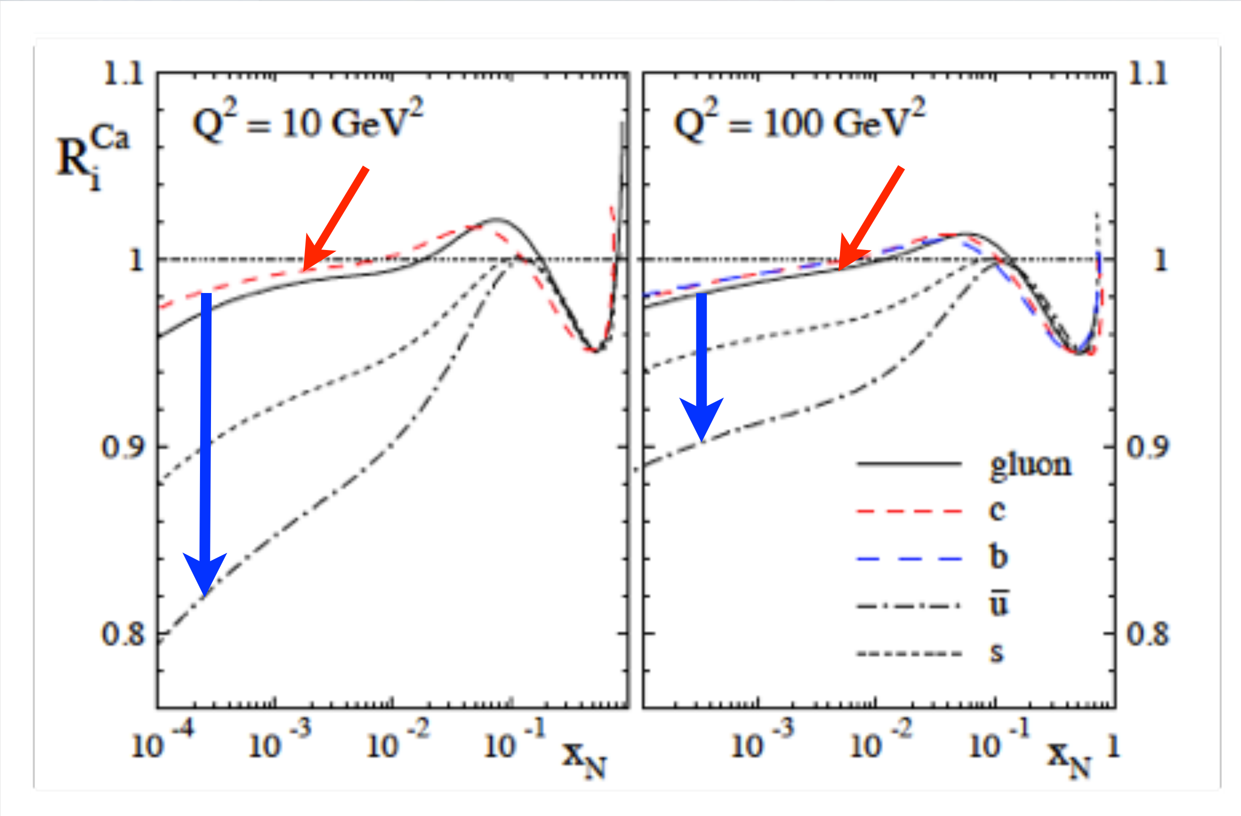

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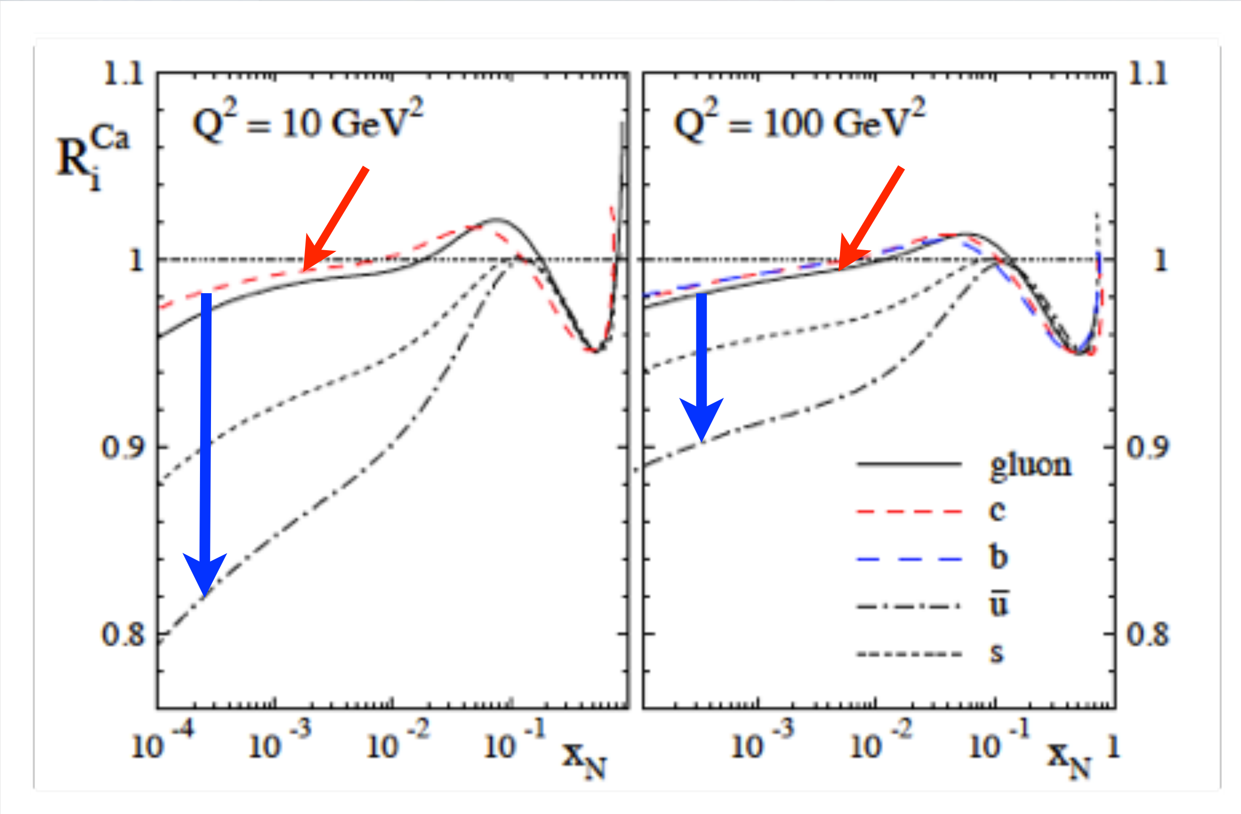

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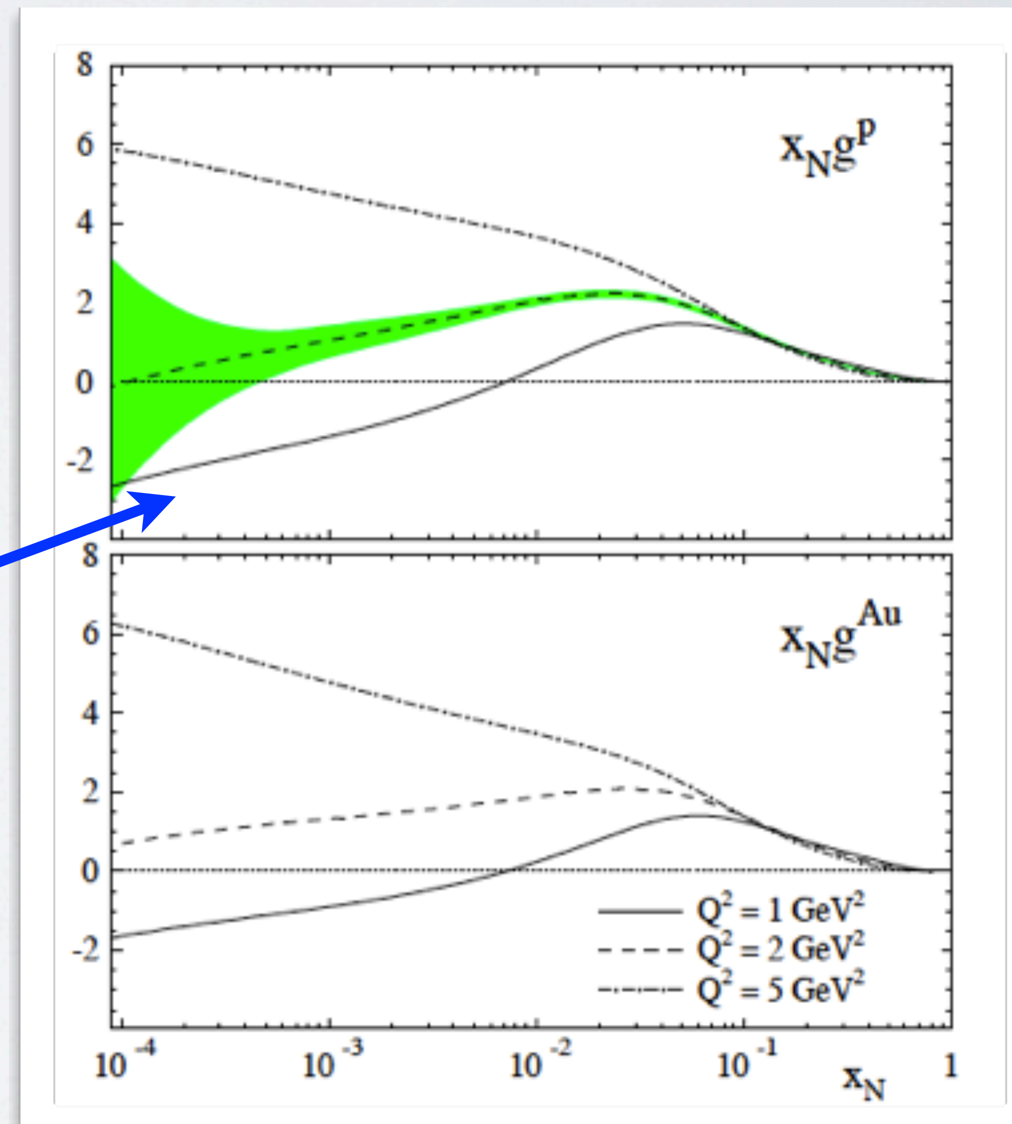

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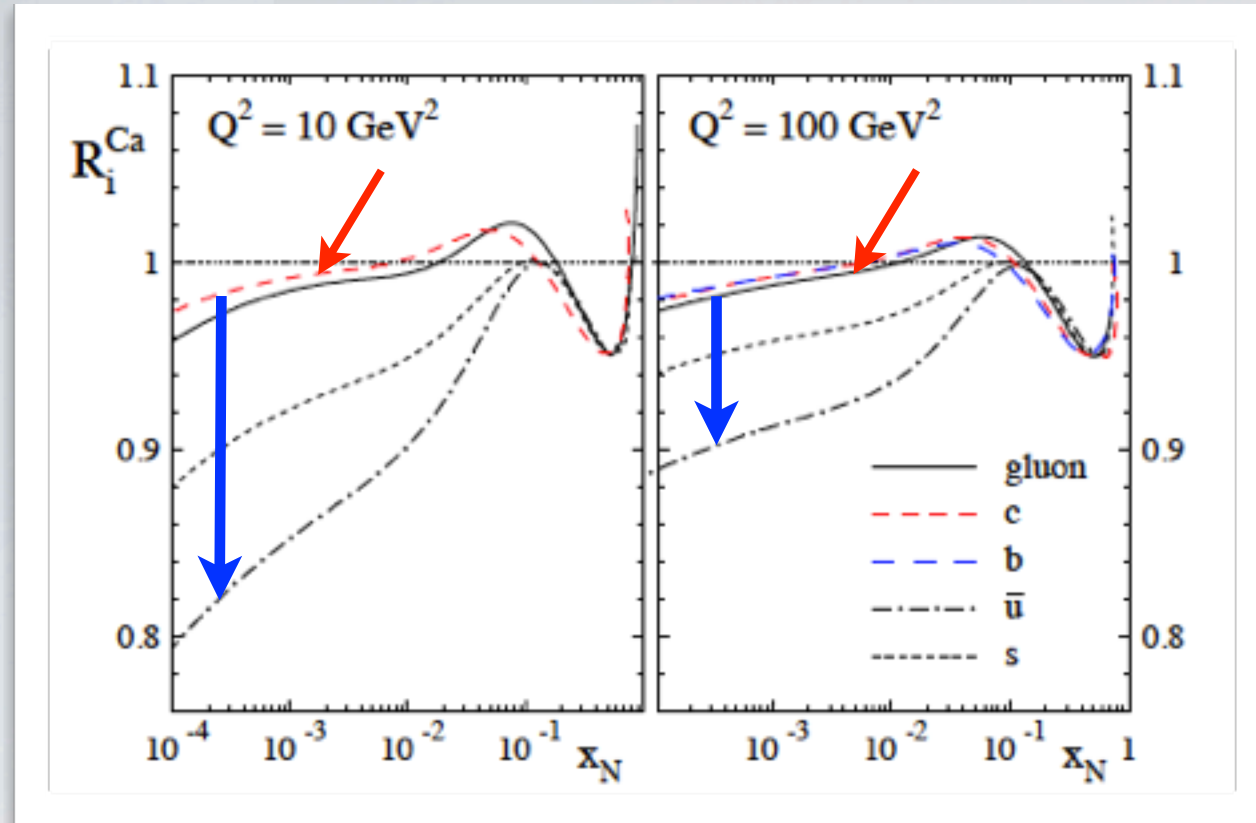

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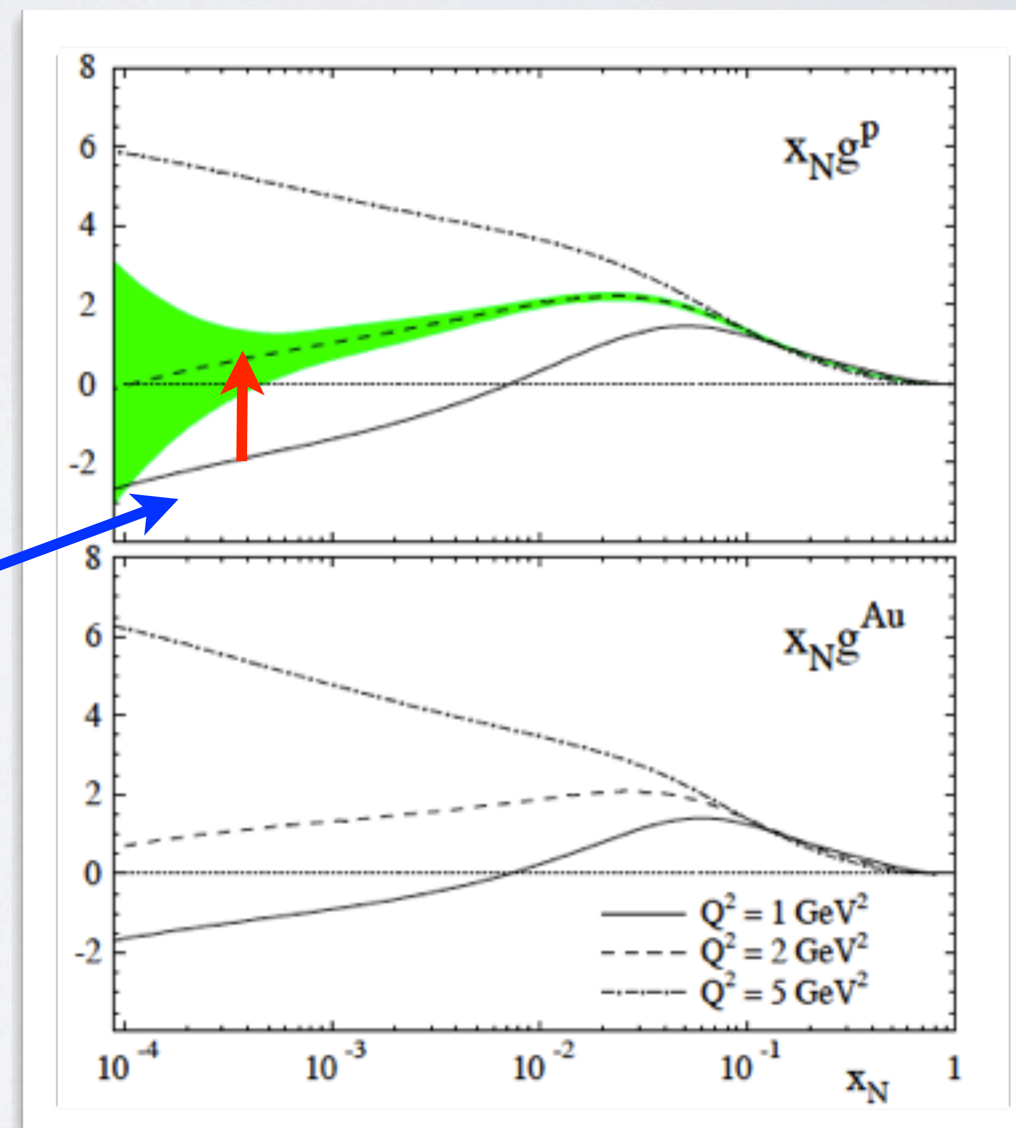

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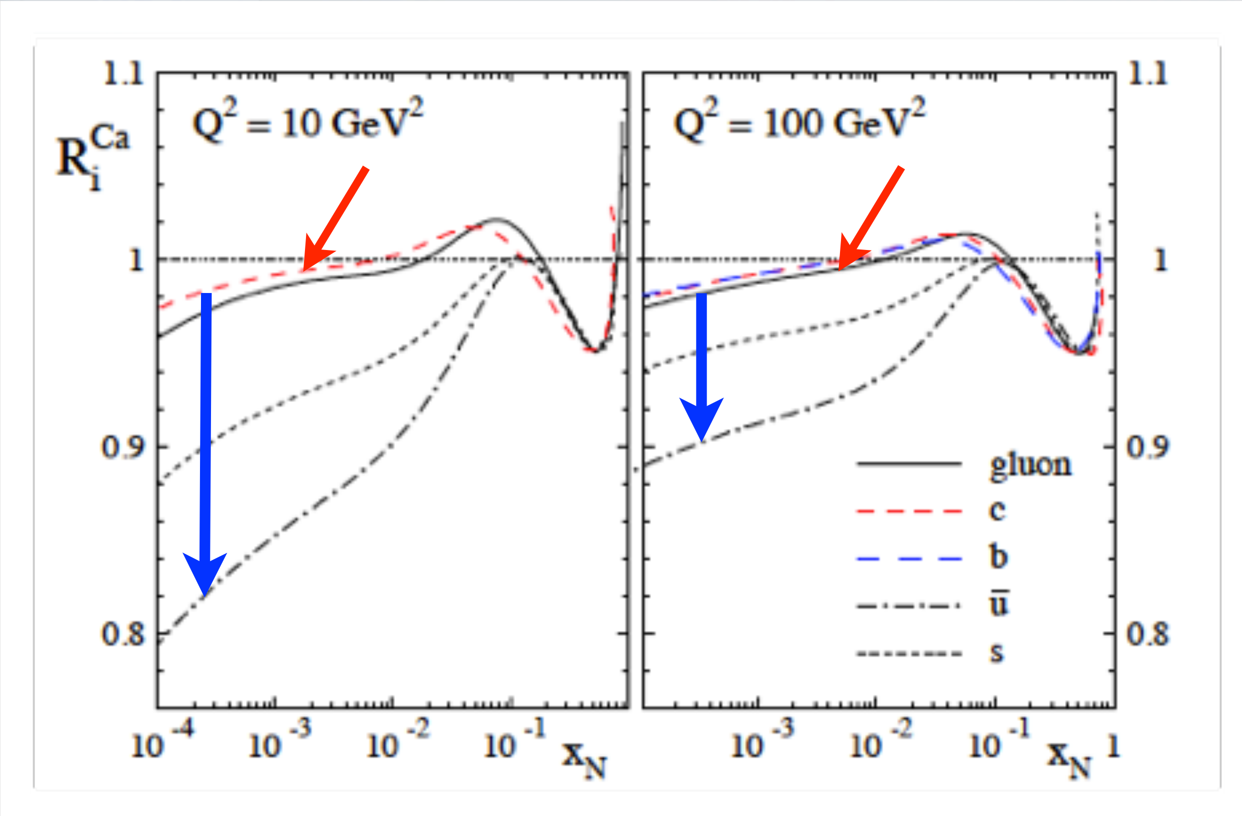

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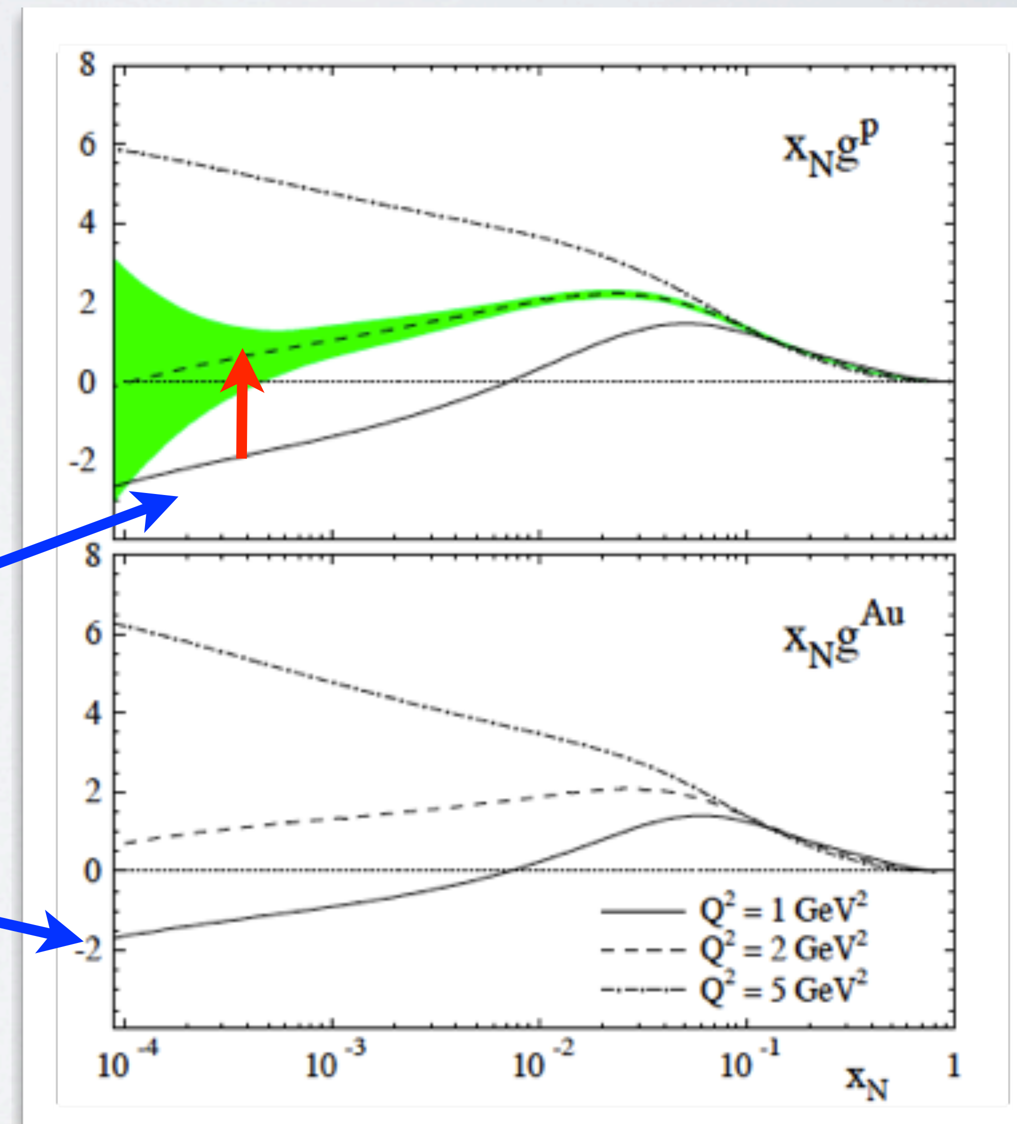

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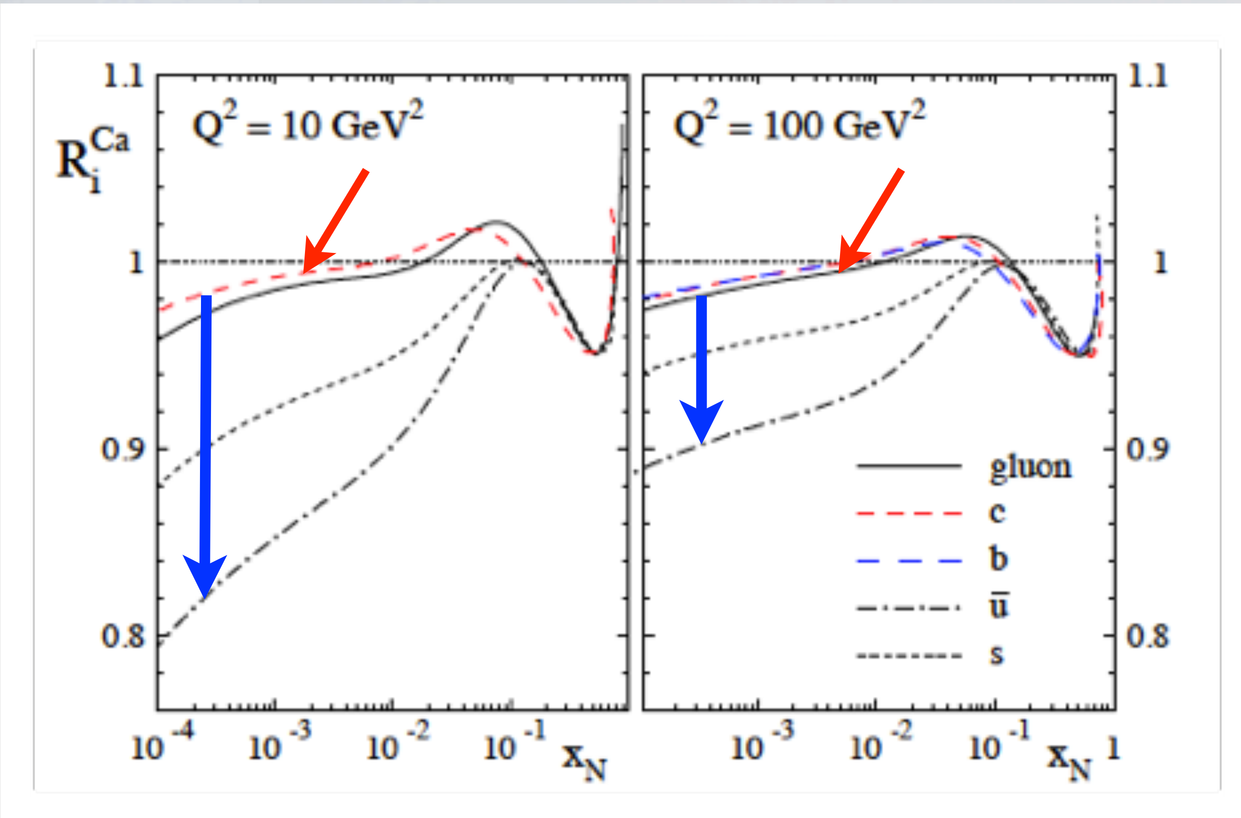

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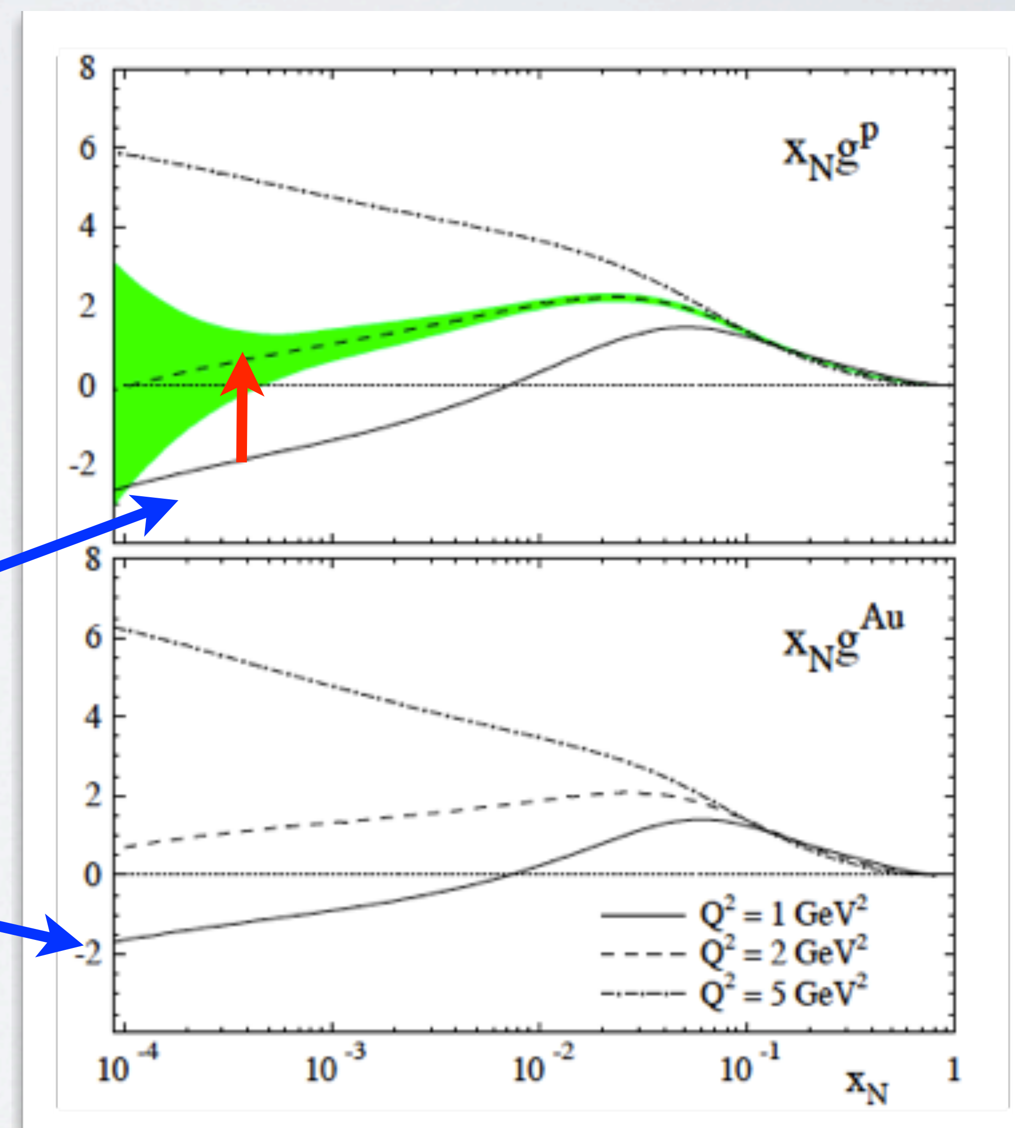
one must take trad. ratios R_i^A with a pinch of salt in NLO



some future avenues for nPDF fits
RHIC & LHC

prompt photons in dAu / pPb

complication: "isospin effects" = dilution of u-quark density from neutrons $\mathbf{u^A(x) < u^p(x)}$

→ ratio dAu/pp not unity even w/o nuclear modifications

see also Arleo et al, 1103.1471

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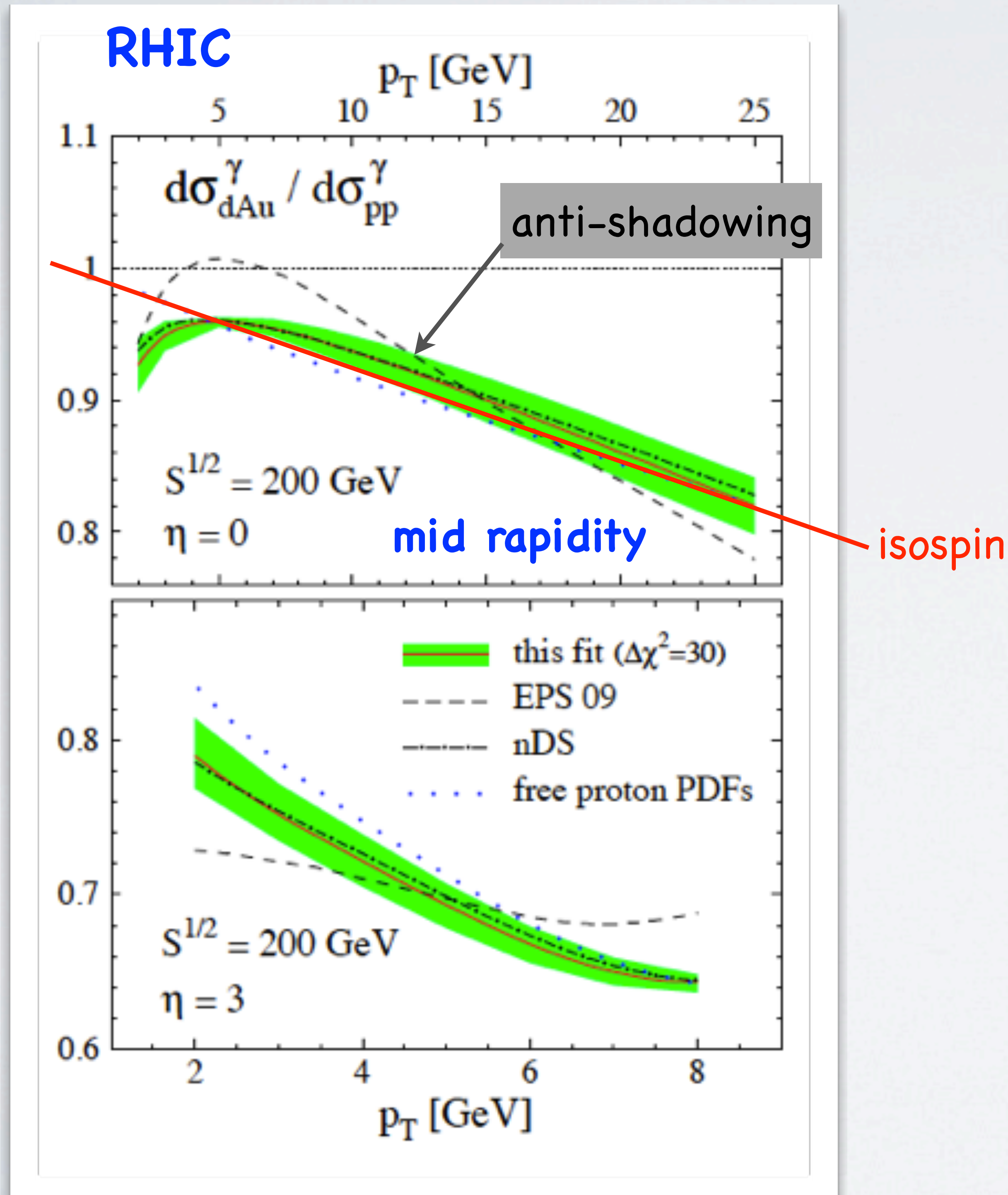

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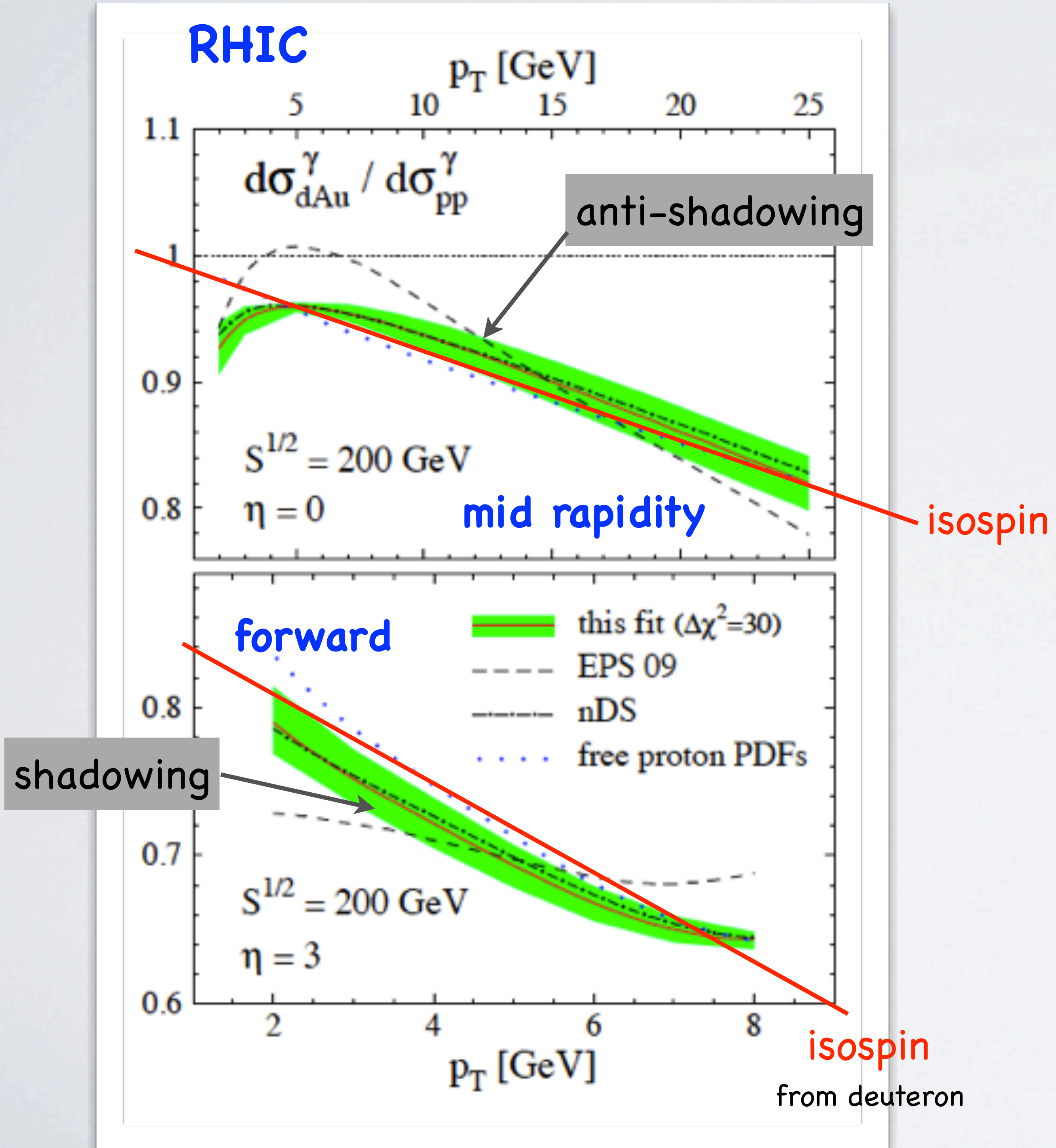

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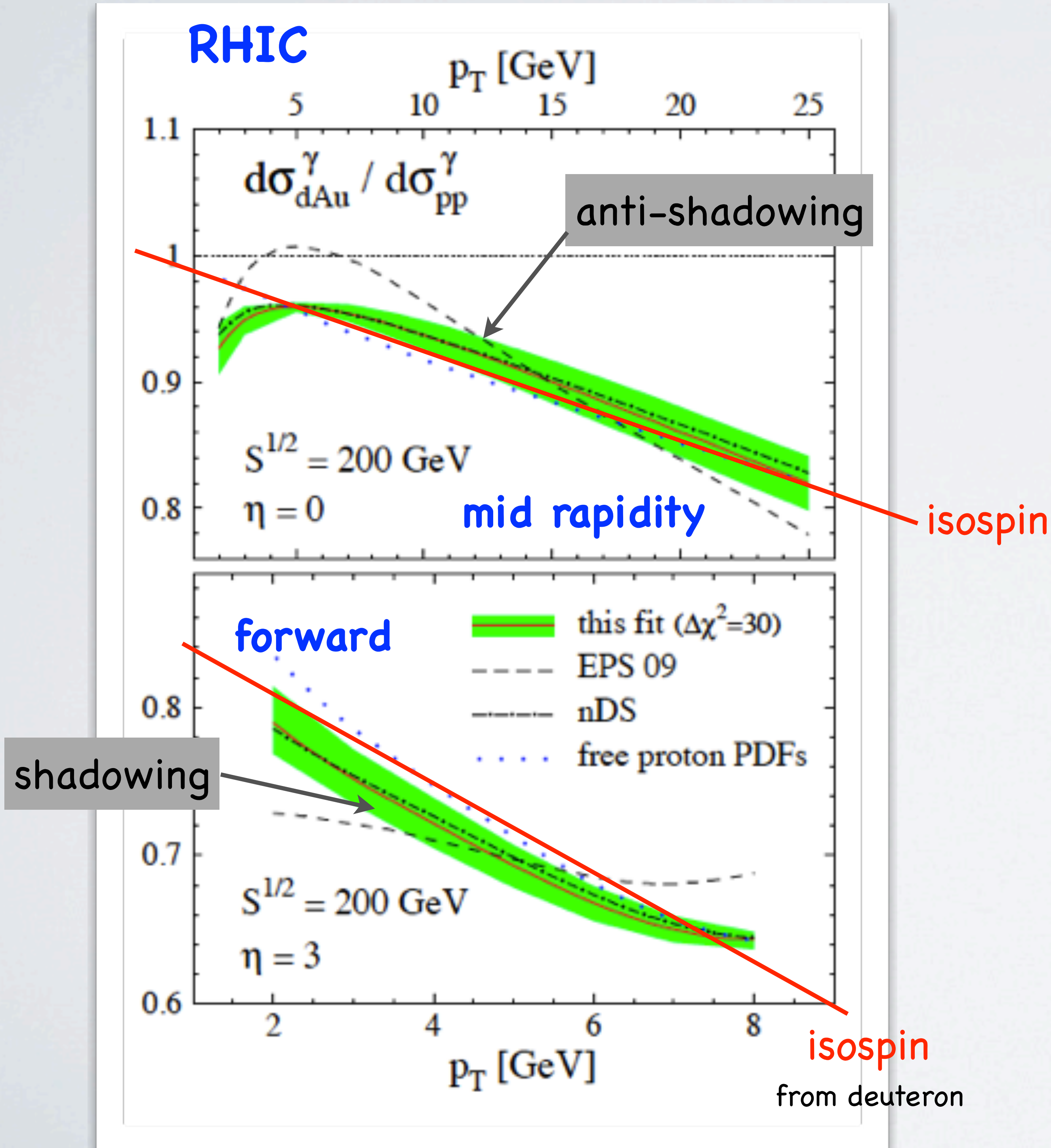

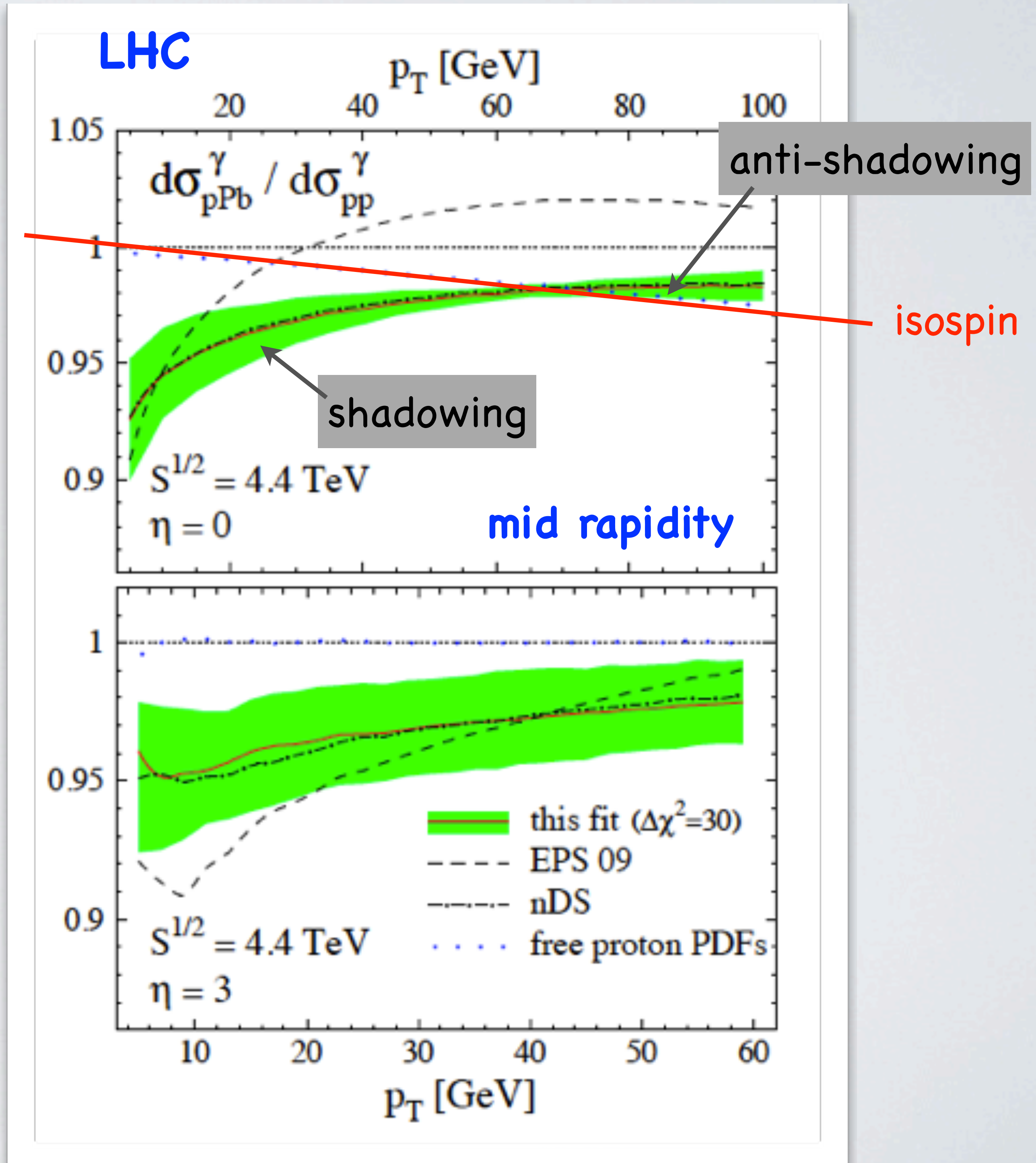

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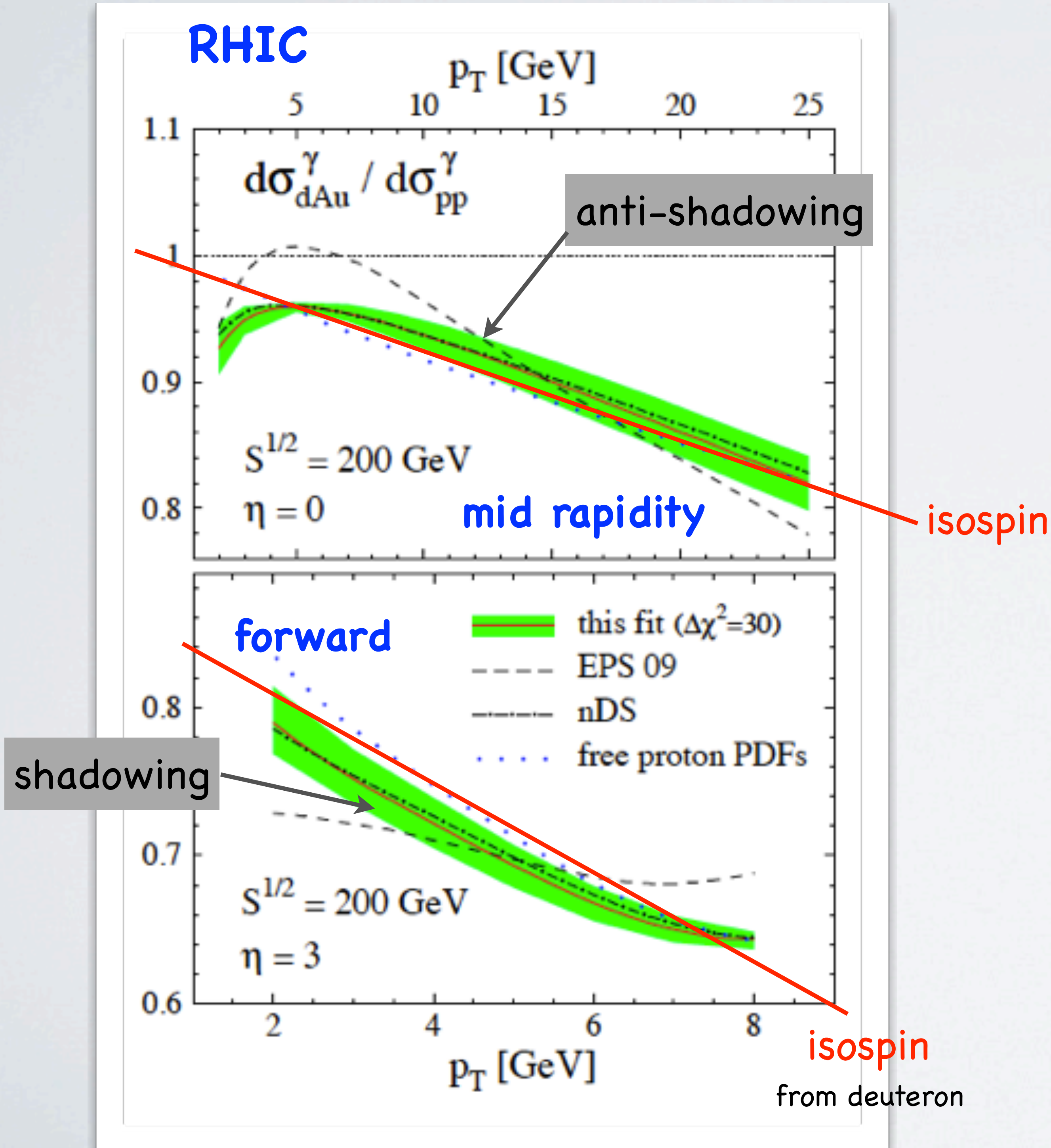

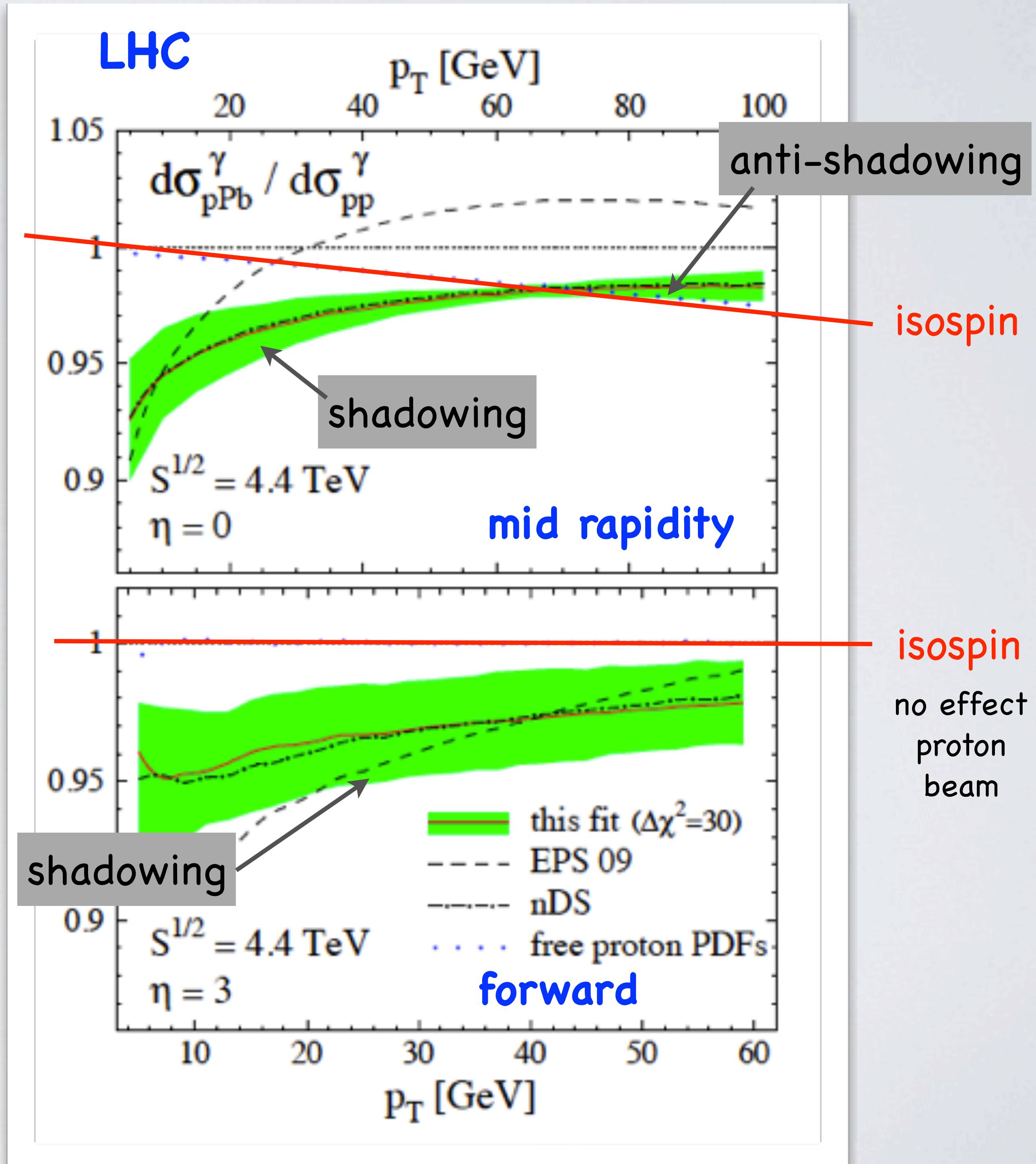

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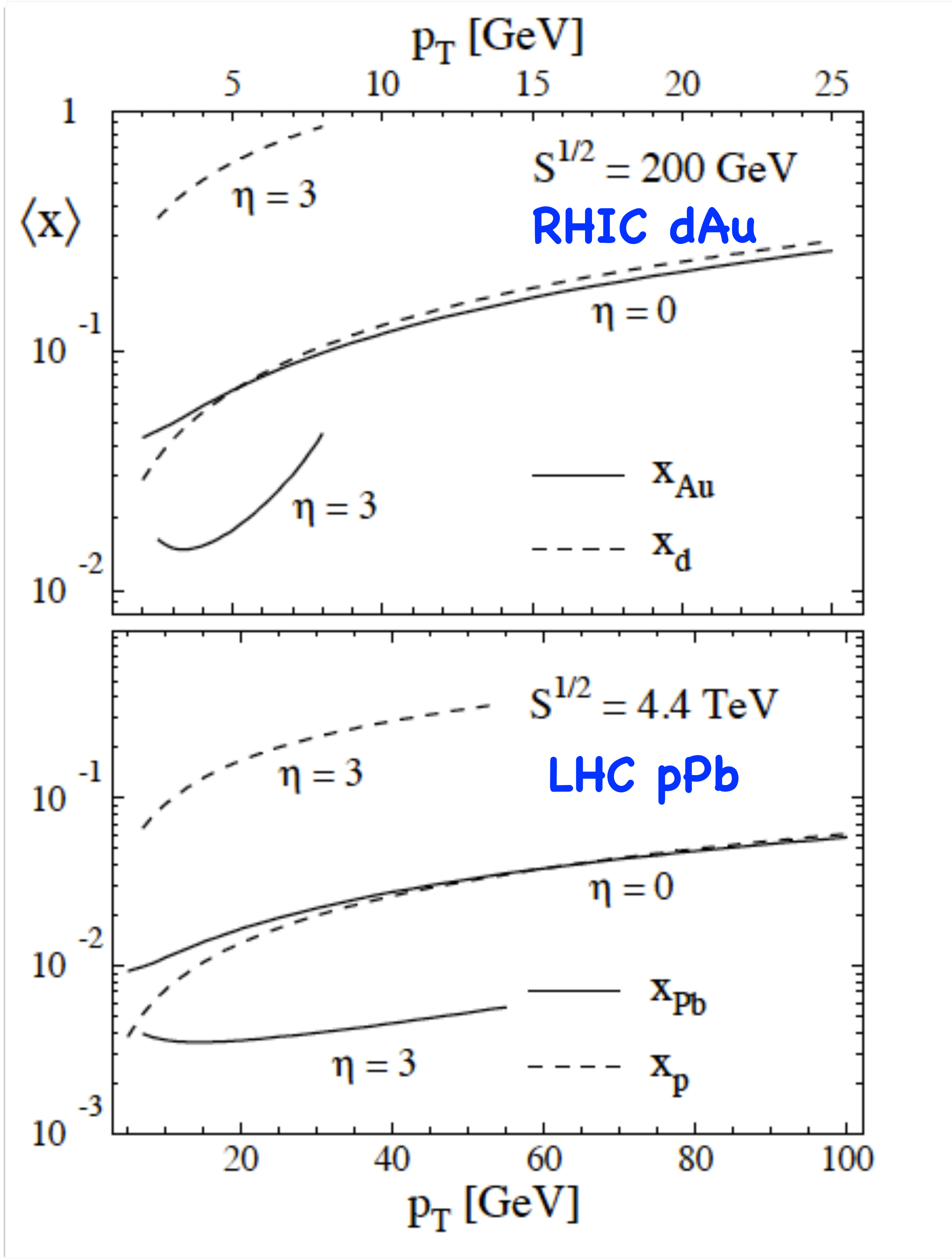
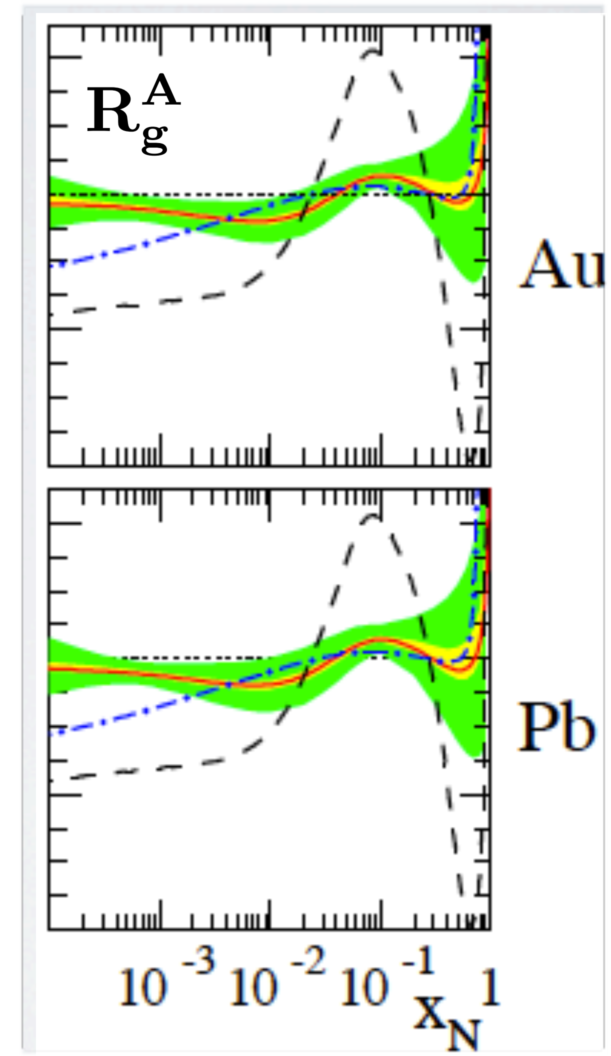
prompt photons - impact





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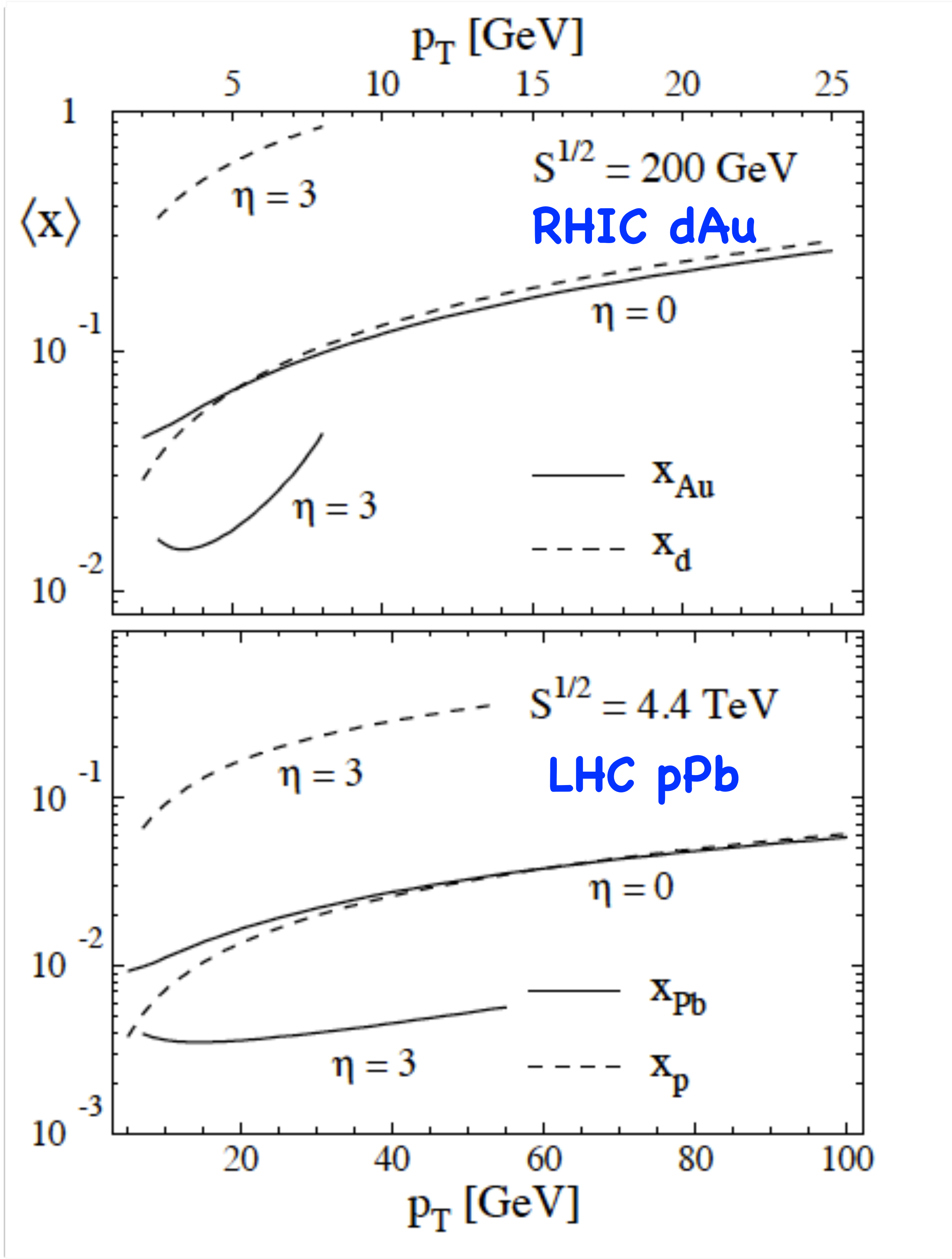
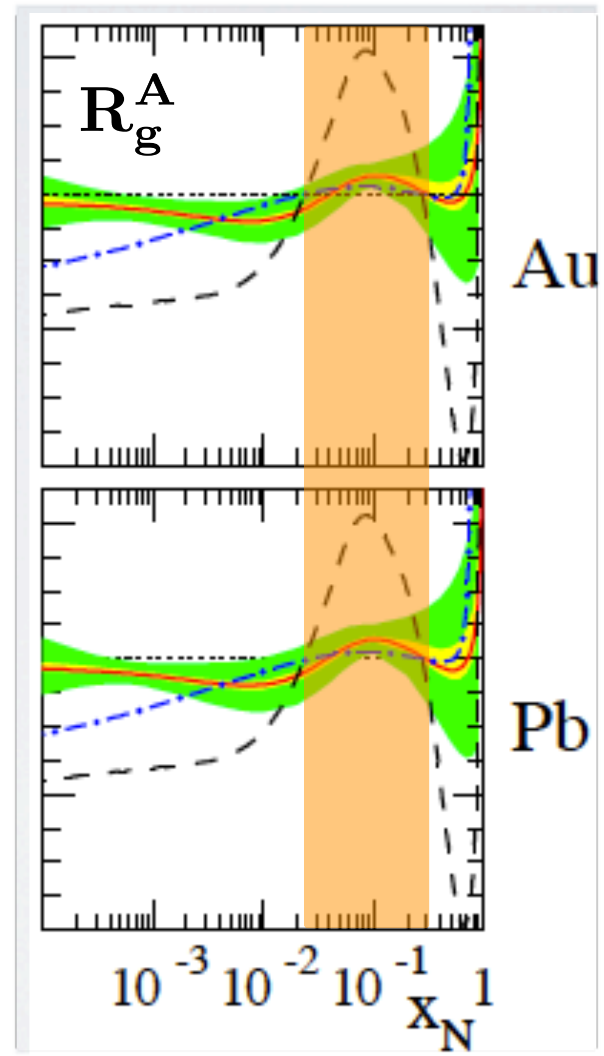


- can resolve characteristic differences between EPS and DSSZ gluons in anti-shadowing [and EMC] region



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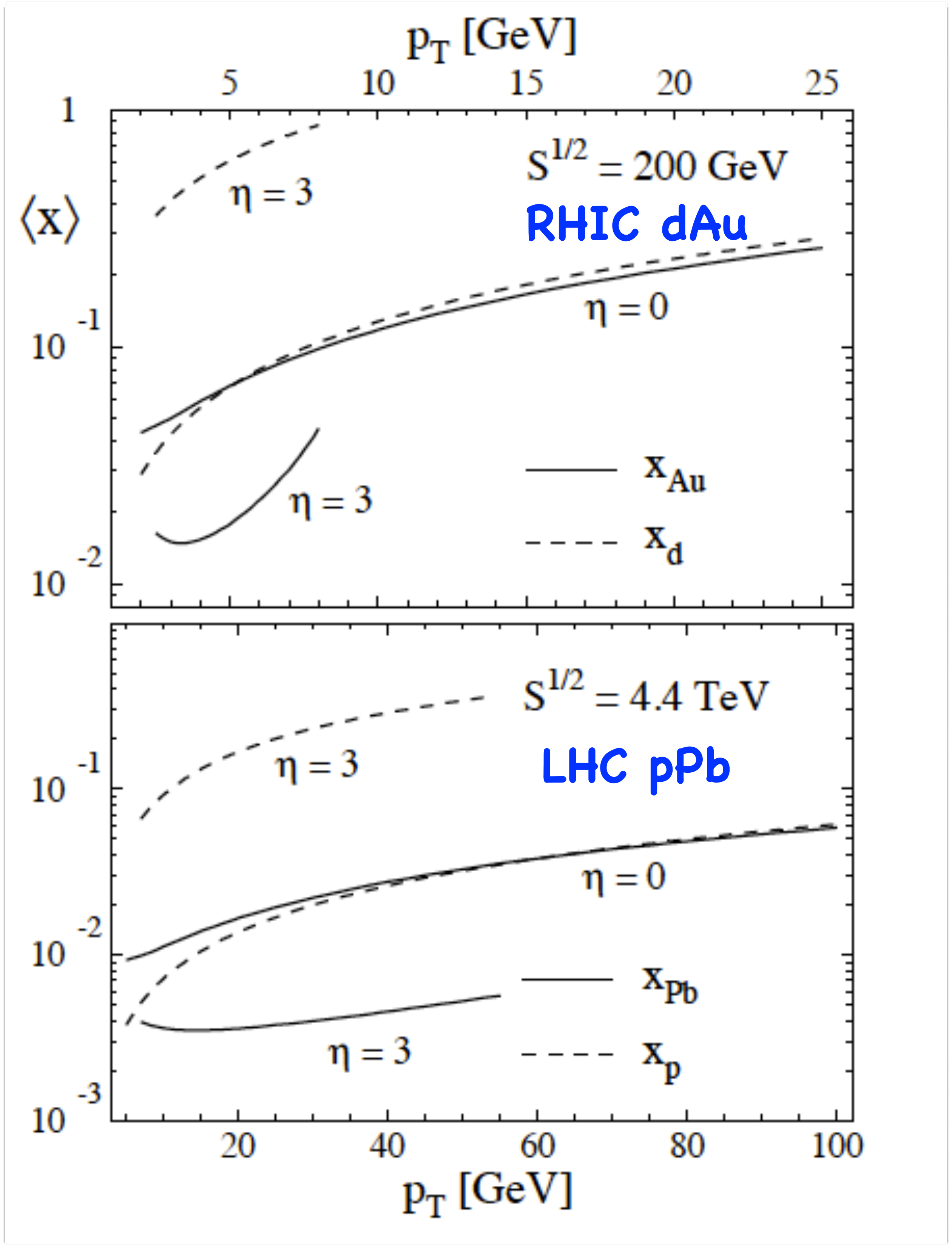

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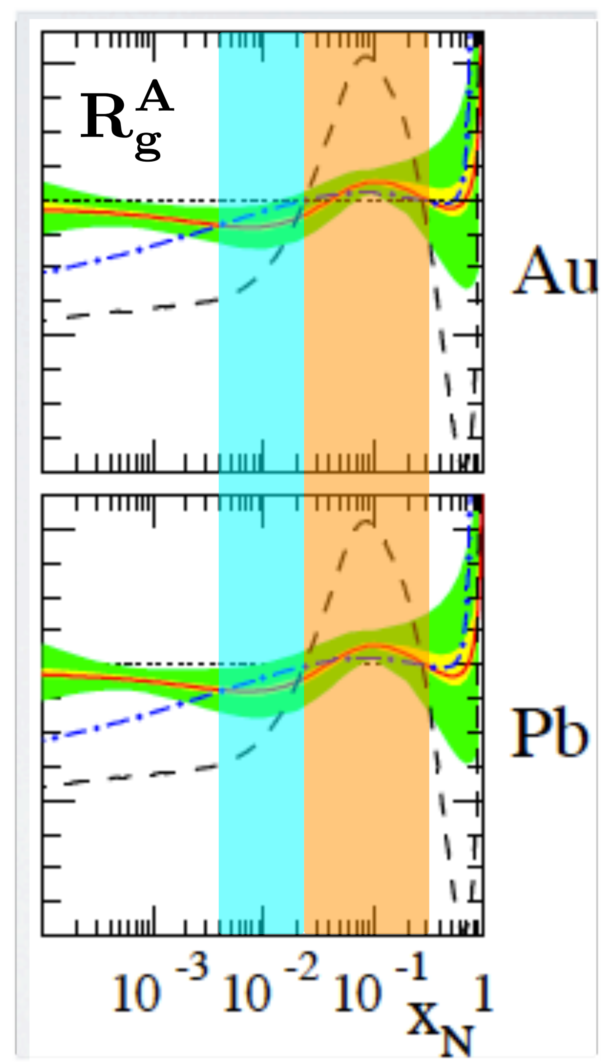
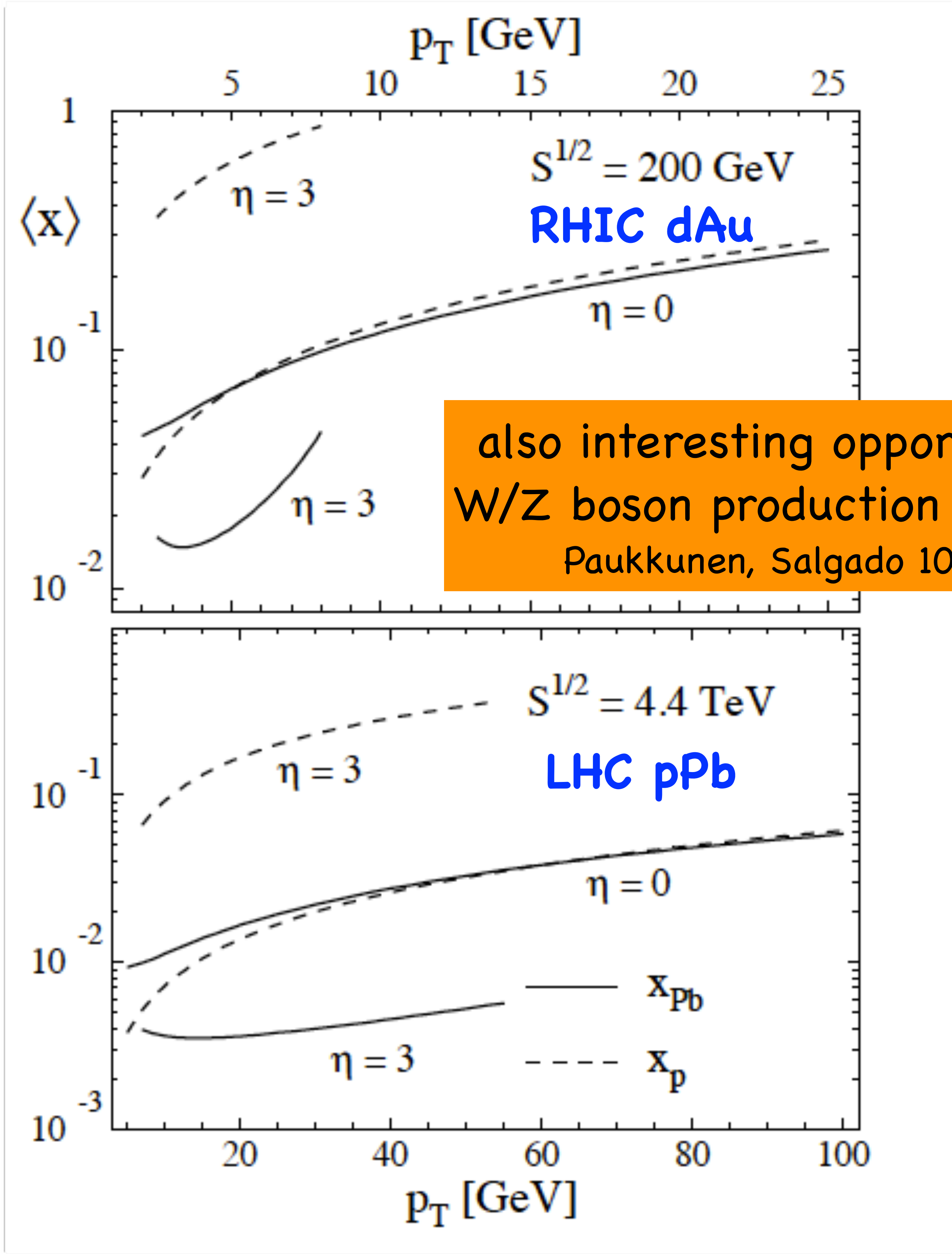


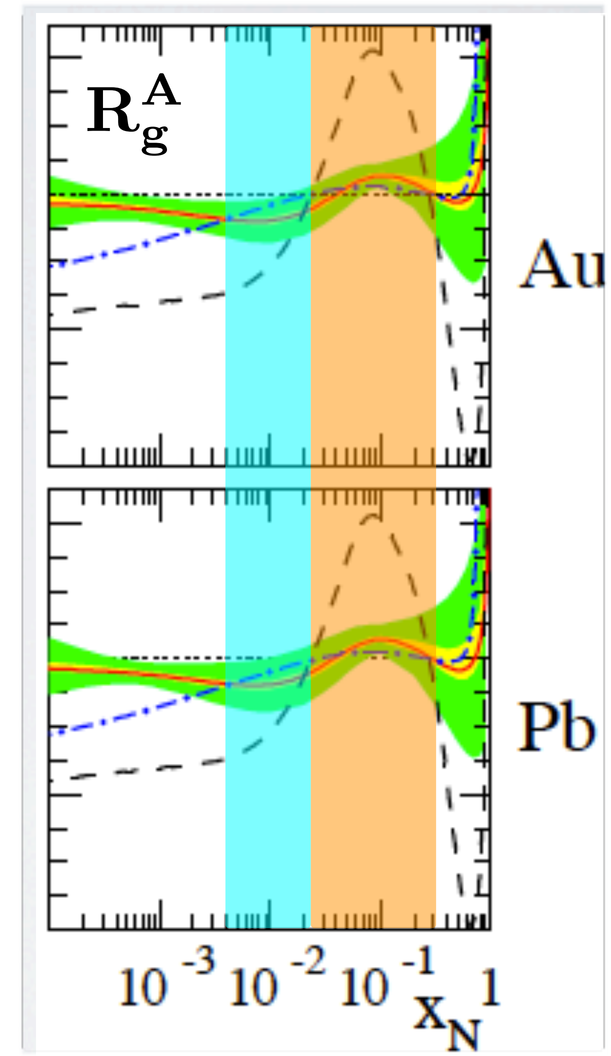
- can probe into shadowing region

prompt photons - impact



also interesting opportunities in W/Z boson production at the LHC
Paukkunen, Salgado 1010.5392

- can resolve characteristic differences between EPS and DSSZ gluons in anti-shadowing [and EMC] region



- can probe into shadowing region

Drell Yan lepton pairs in dAu/pPb

LO $$\mathbf{d\sigma^{pA}_{DY} \propto e_u^2 \left[u(x_1)\bar{u}^A(x_2) + \bar{u}(x_1)u^A(x_2)\right] + e_d^2 \left[d(x_1)\bar{d}^A(x_2) + \bar{d}(x_1)d^A(x_2)\right]}$$

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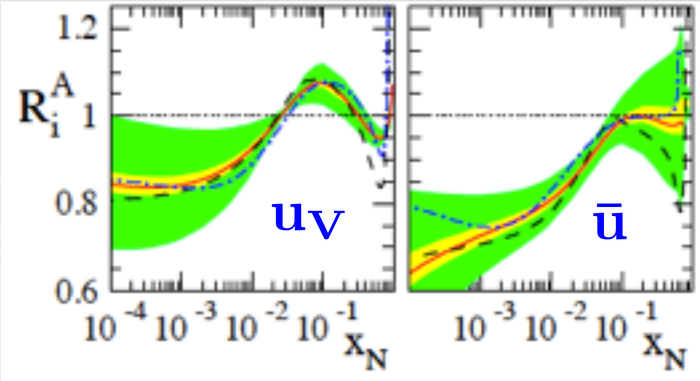

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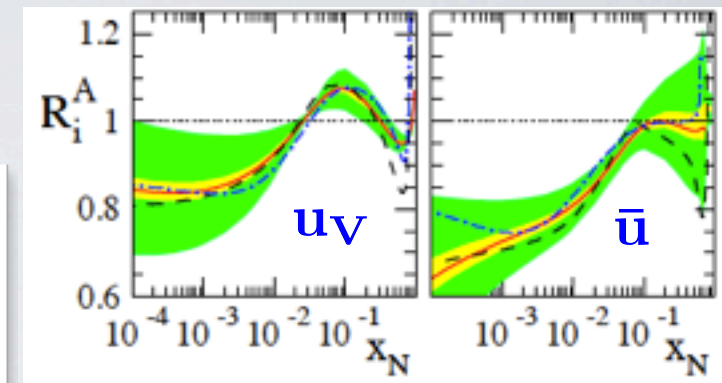

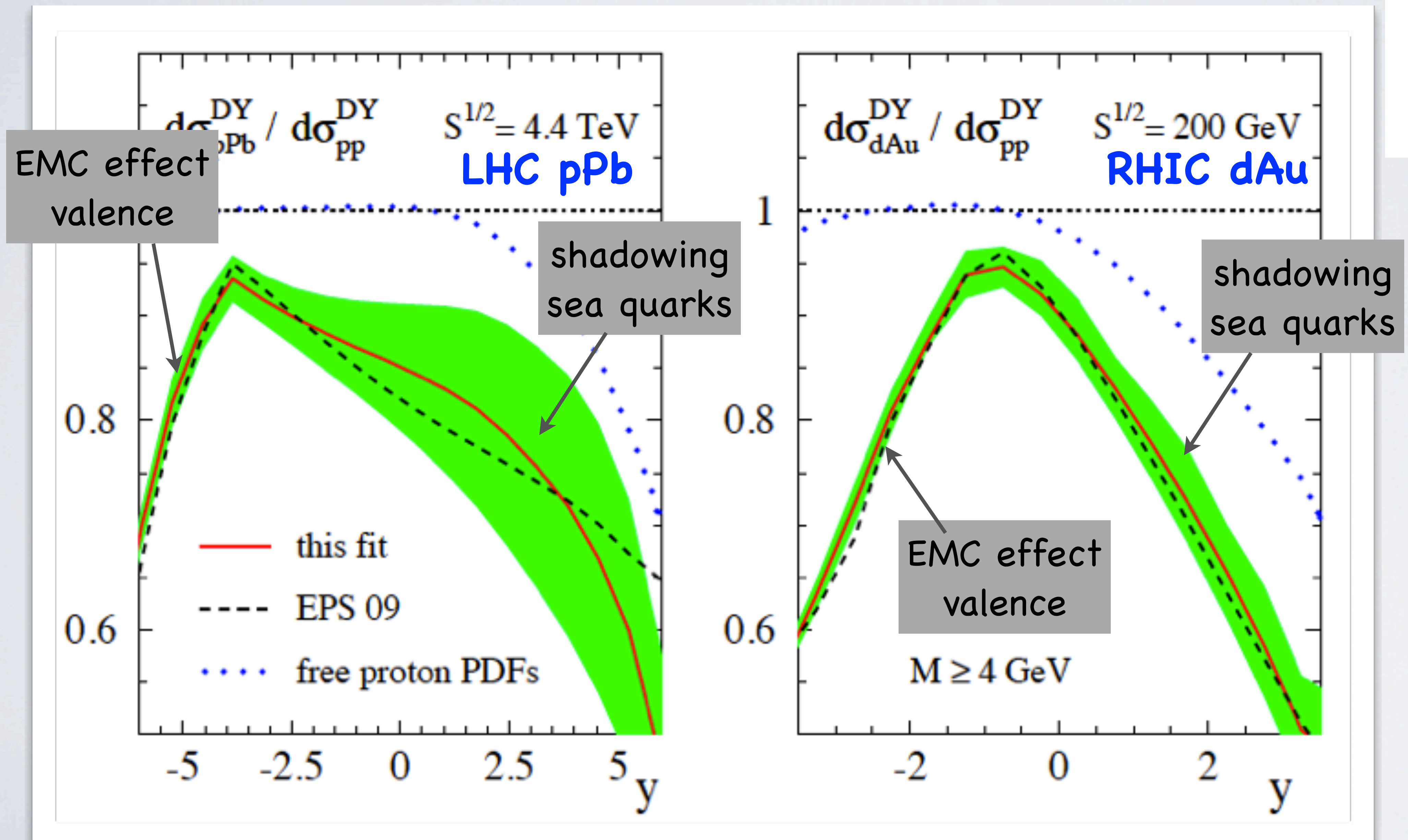

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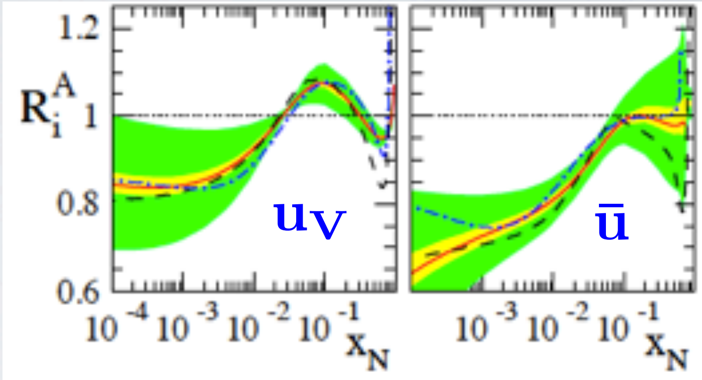
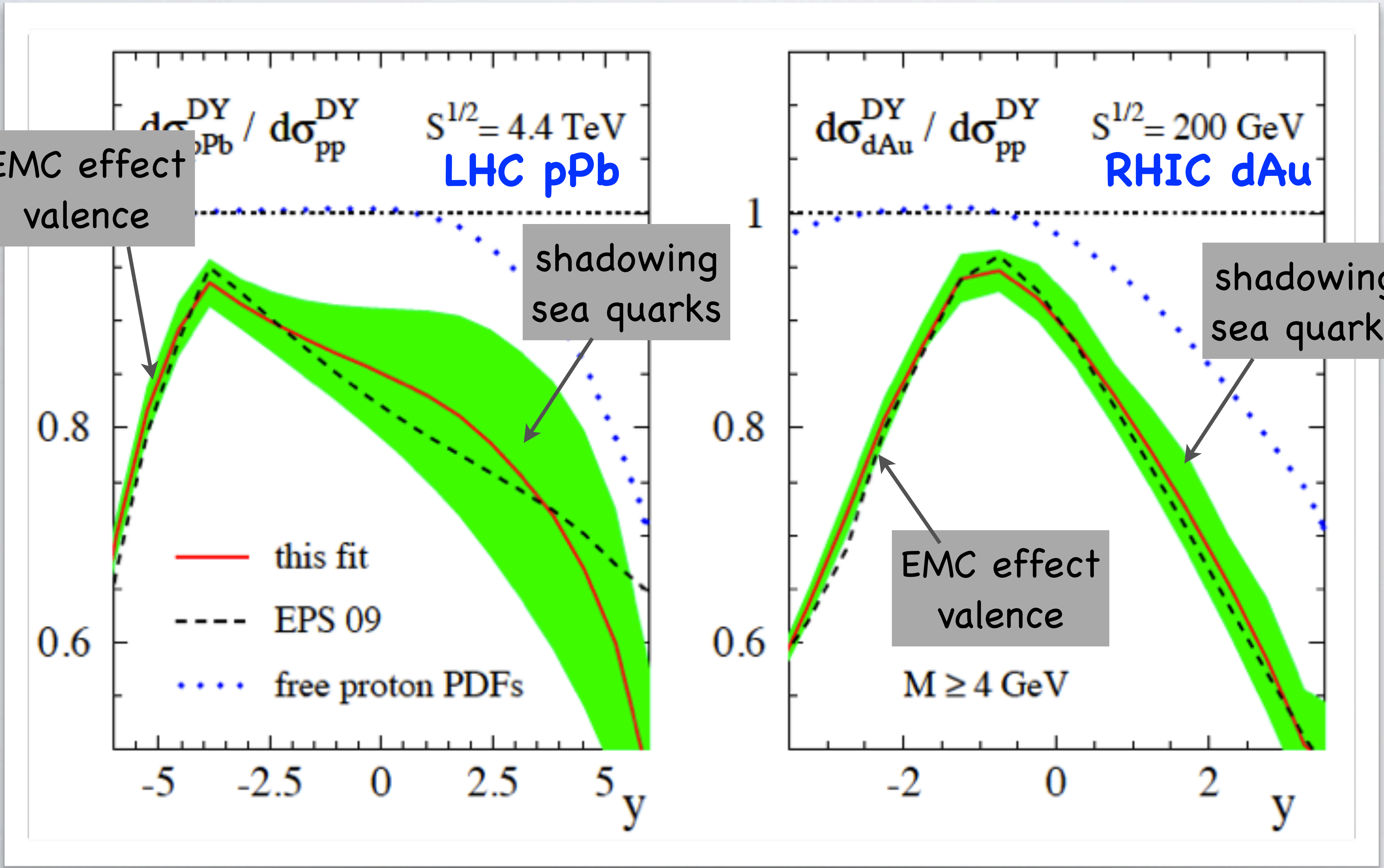




x reach at y=3

RHIC: $x_2 \simeq 10^{-3}$

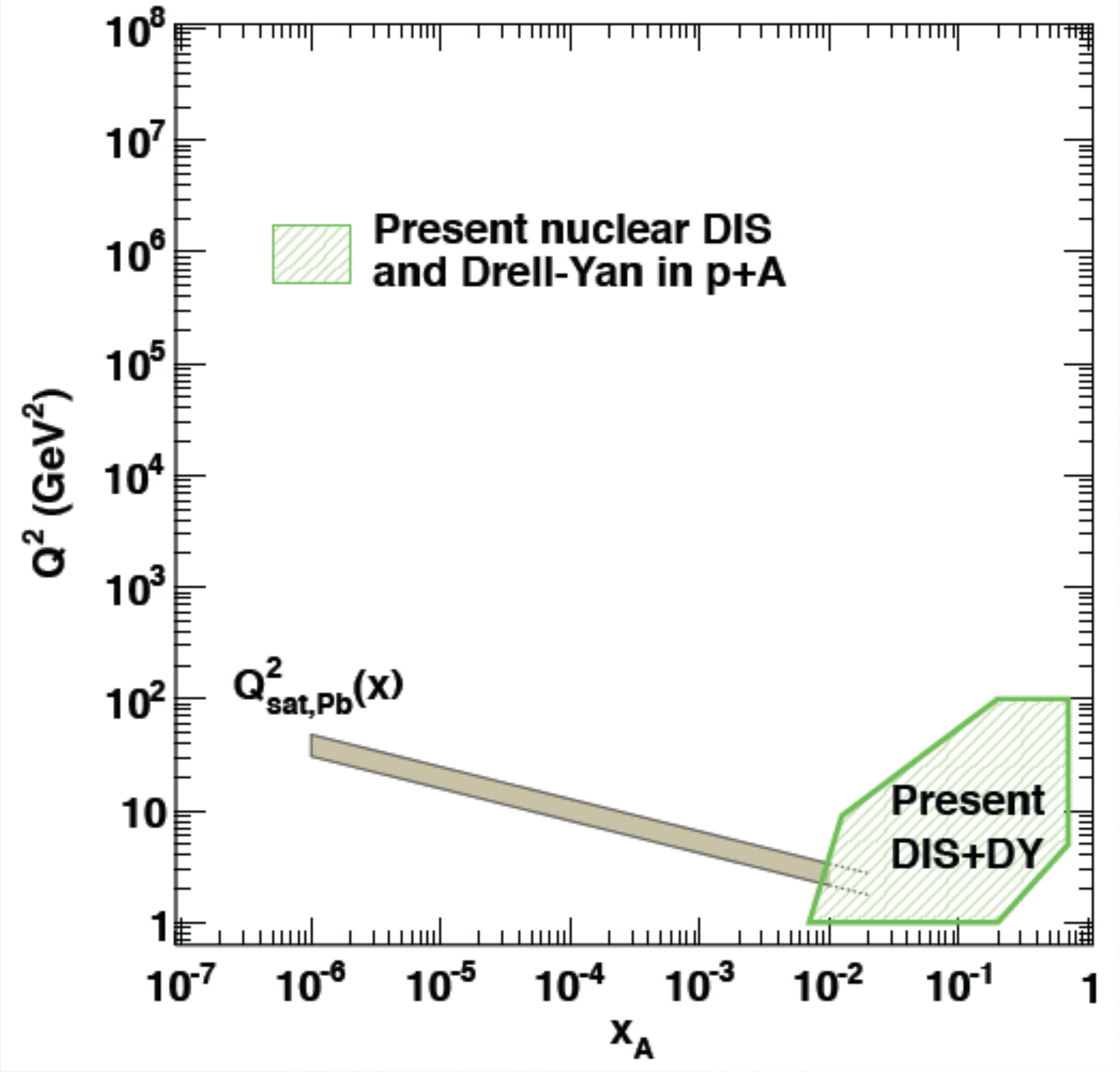
LHC: $x_2 \simeq 5 \times 10^{-5}$

potential of pPb @ LHC

first run scheduled for early 2013

see Salgado et al., 1105.3919

kinematic reach



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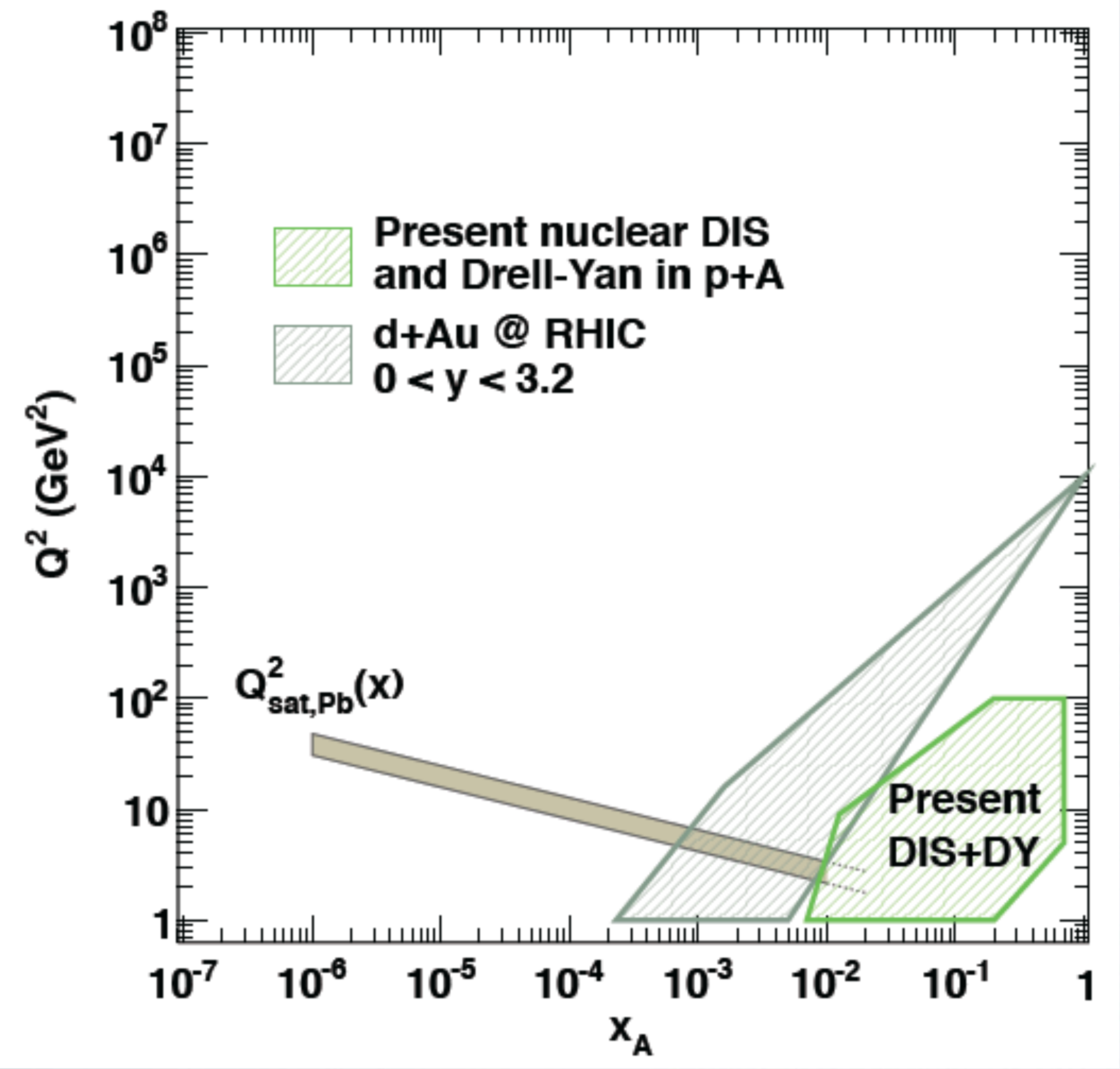

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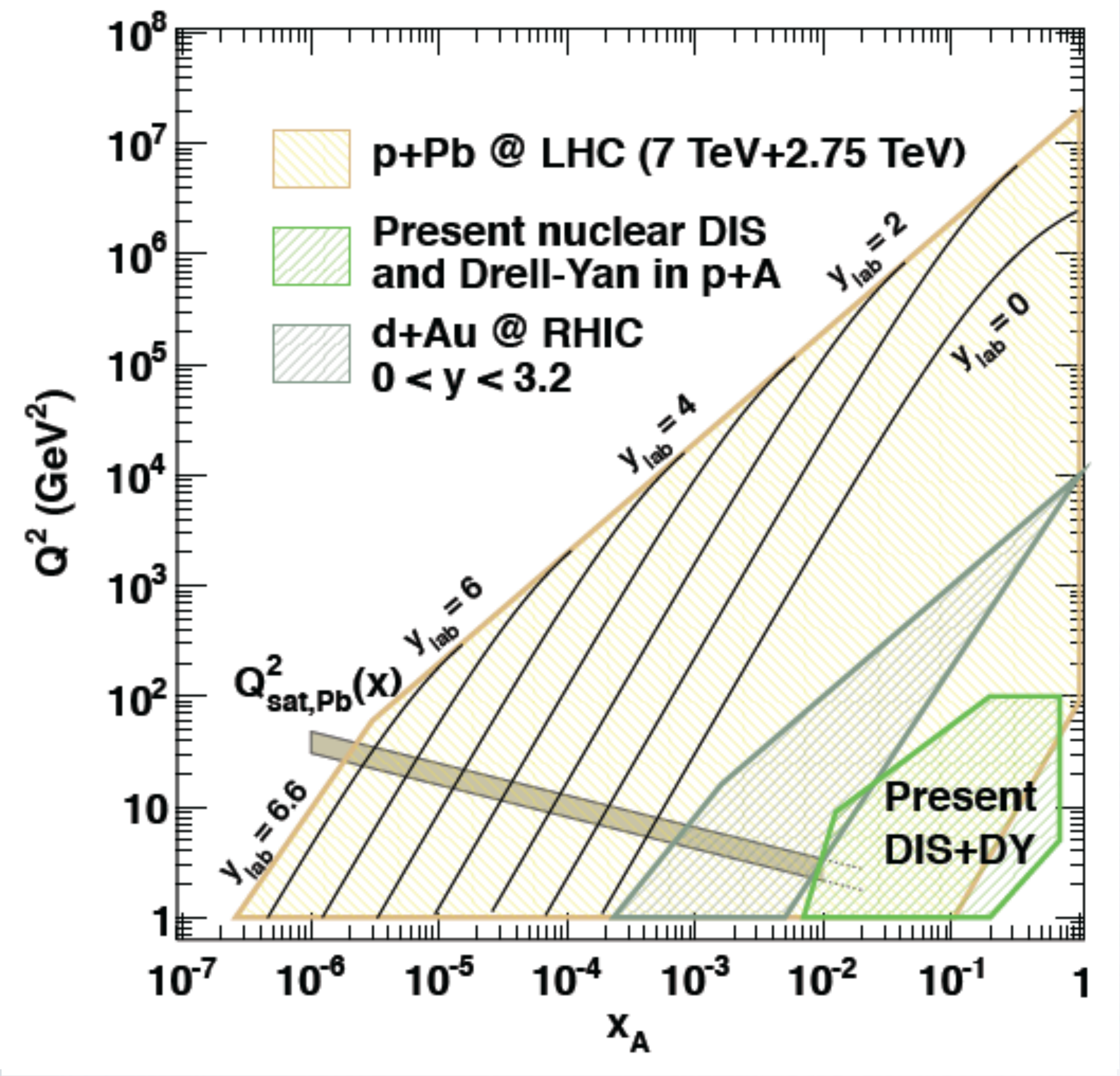

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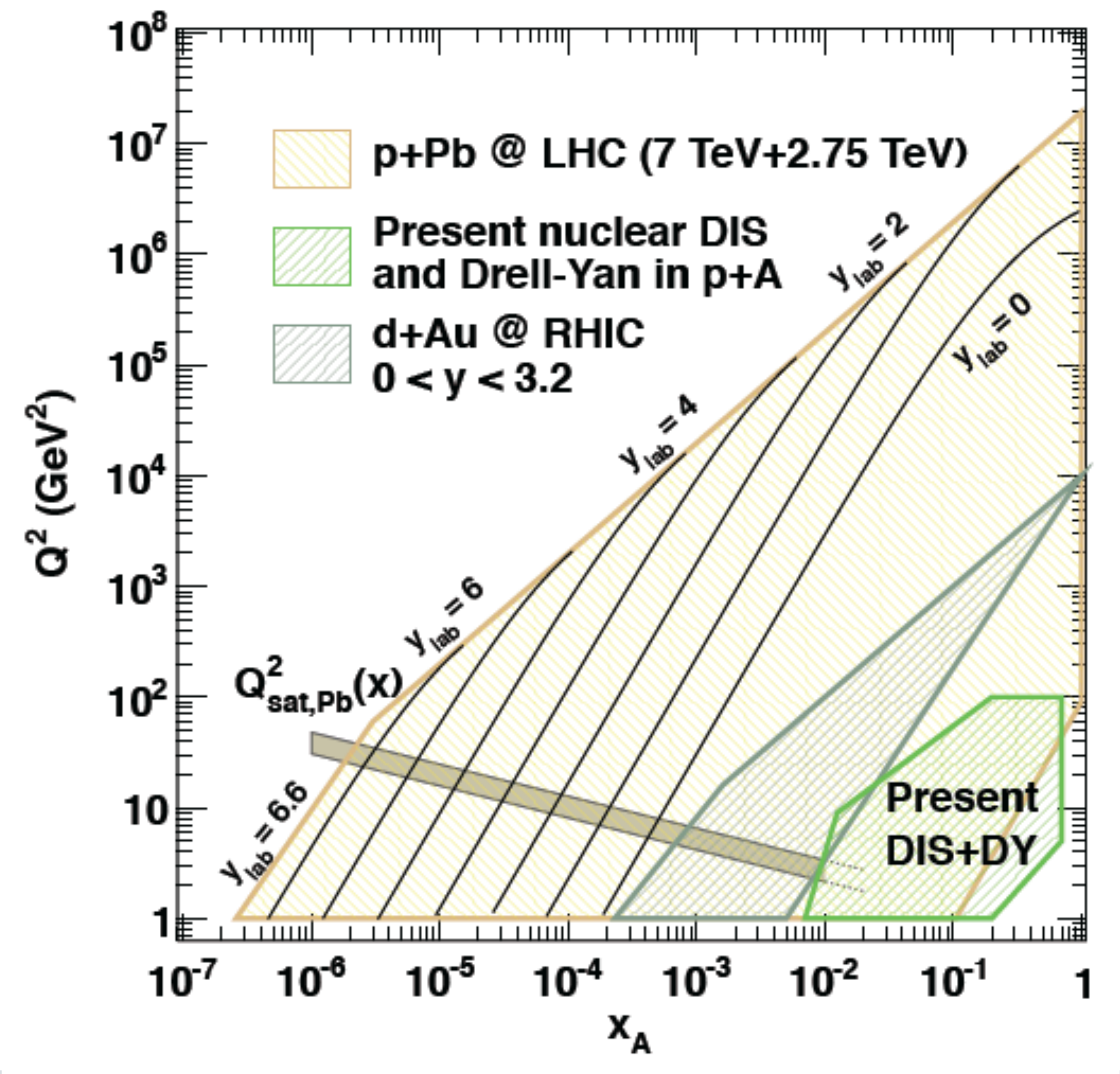

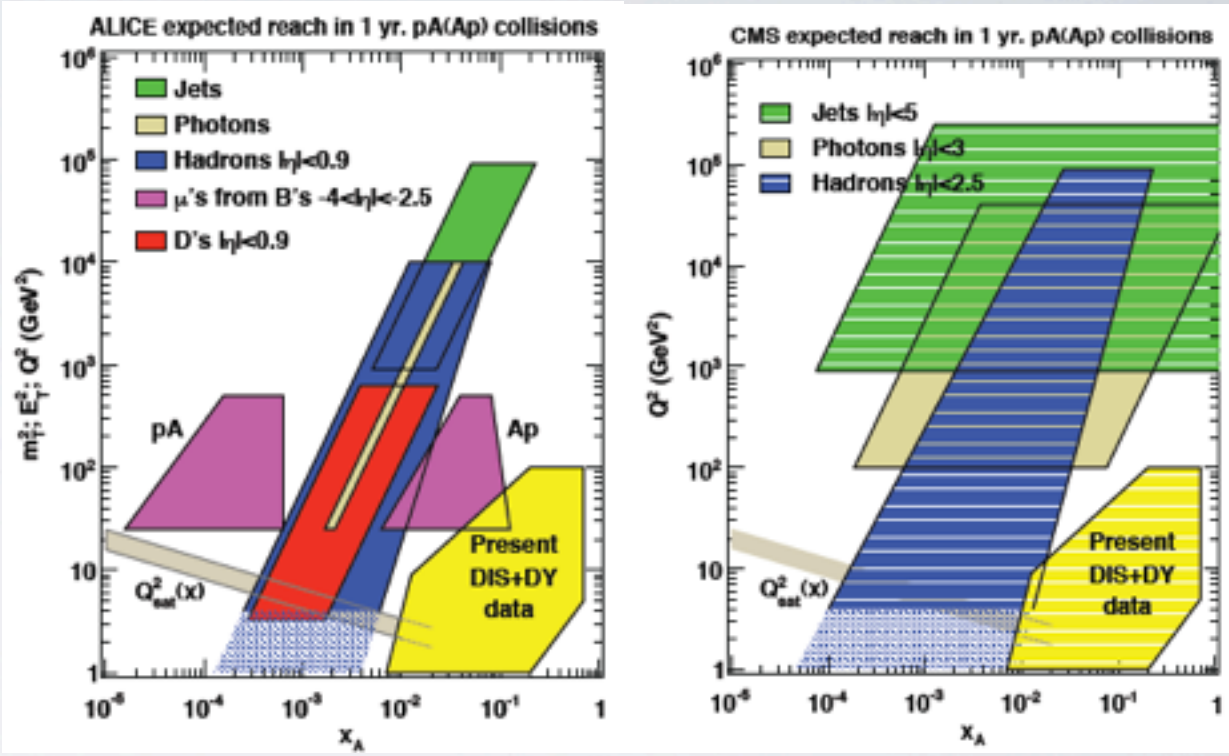

- small x already accessible at mid rapidity
- many conceivable probes

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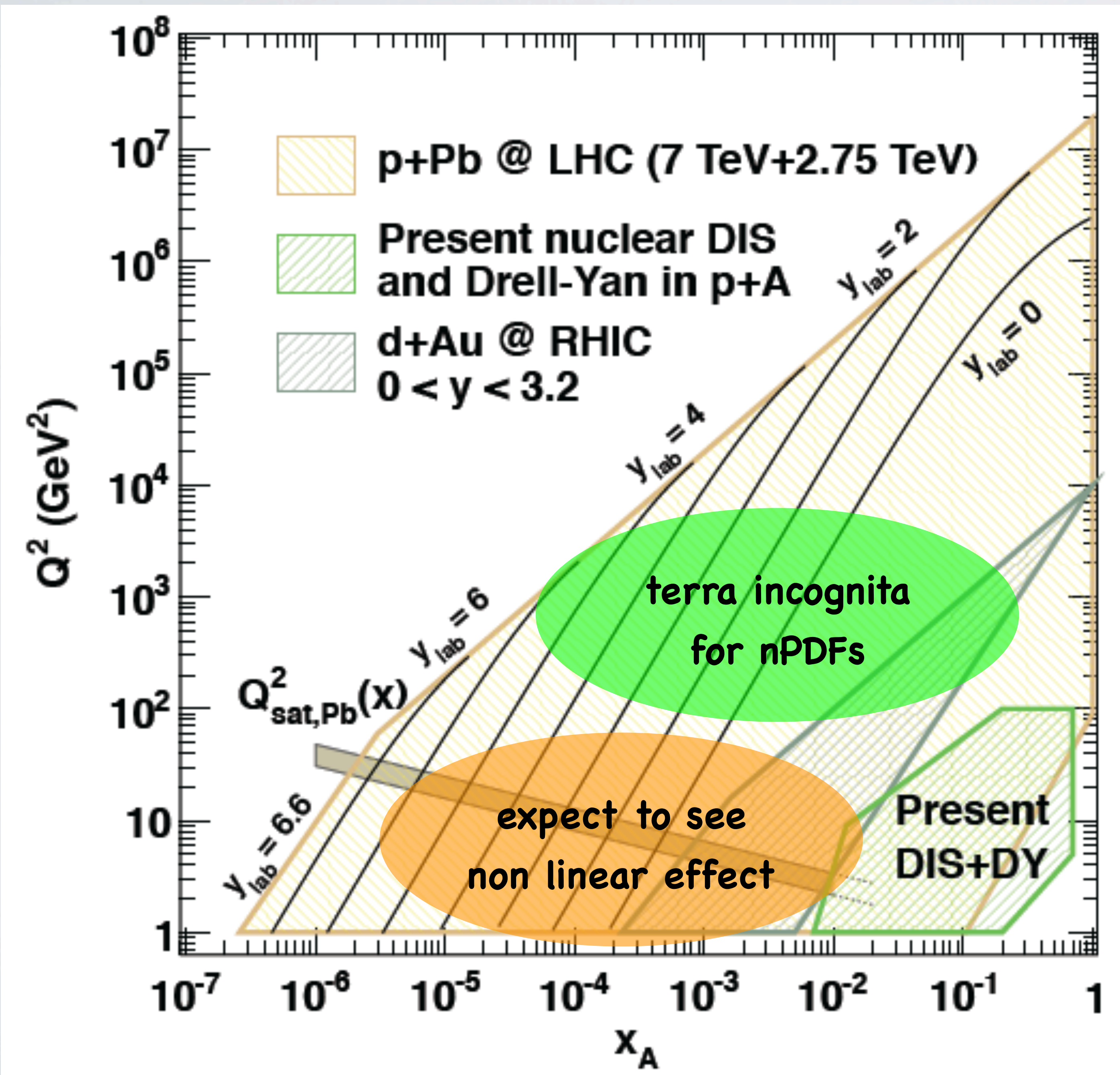

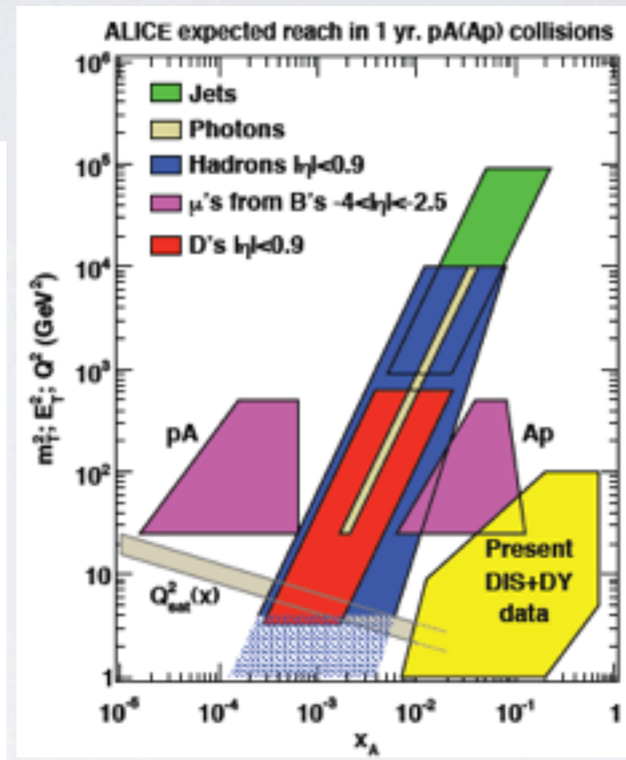

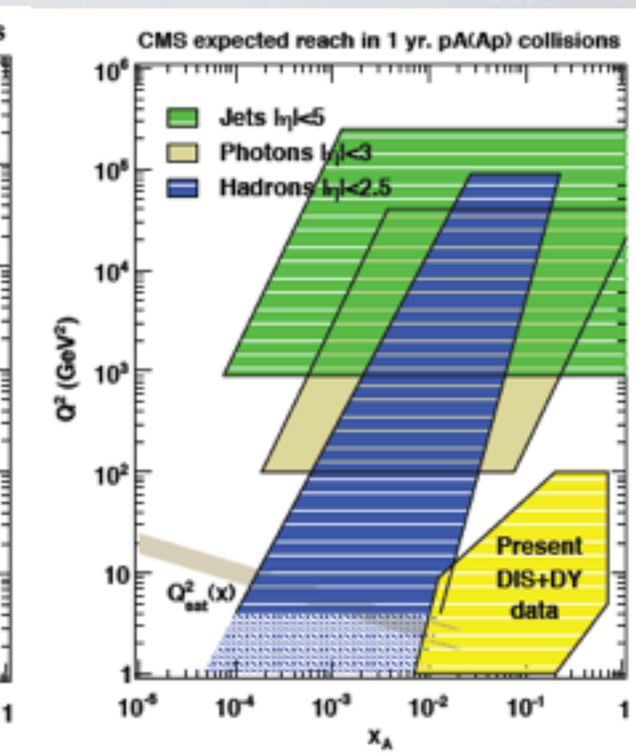

- small x already accessible at mid rapidity
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expect great impact on nPDF fits

take away message

- **first fully global QCD analysis of nuclear PDFs at NLO**
  includes charged lepton DIS, neutrino DIS, Drell Yan, and dAu pion data

- **main observations**
  no tension with neutrino DIS data (unlike in nCTEQ fit)
  much more moderate modifications of gluon from RHIC data (unlike in EPS fit)

- **technical advances**
  treatment of heavy quark mass effects
  use of numerical efficient Mellin technique throughout
  uncertainty estimates with improved Hessian method (eigenvector/error sets)

- **exciting prospects for upcoming LHC pPb and future RHIC runs**
  impact of electromagnetic probes (prompt photons and Drell Yan)

more distant future: electron-ion collider (EIC/LHeC)

to study nPDFs, universality, factorization, and the transition to saturation with precision